Magnetic moment of the 3^- level of ^{40}Ca from magnetic decoupling in free ions*

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The method of magnetic decoupling of hyperfine fields in free ions is used to estimate the magnetic moment of the lowest 3^- level of ^{40}Ca ($\tau = 61$ psec). The value $\mu = +0.56 \pm 0.13$ (where the sign is derived from an earlier measurement) confirms the basic nature of this state.

[NUCLEAR REACTIONS ^{40}Ca(α, α'), E=16.17 MeV; measured ($\alpha, \alpha'\gamma$) correlation vs decoupling field H for free ion recoil. 3^- level ^{40}Ca deduced magnetic moment μ. Natural thin targets.]

Previous experiments[1-3] have demonstrated the feasibility of using external magnetic fields to decouple the magnetic hyperfine interaction in free ions as a means of measuring nuclear g factors. In this paper we report the use of this method on hyperfine interactions involving mainly the atomic M shell to measure the g factor of the second excited state of ^{40}Ca ($I^\pi = 3^-$, $E_x = 3.737$ MeV, $\tau = 61$ psec).

The method consists of exciting and orienting the nuclear state of interest by means of a nuclear reaction which also ejects the atoms from a thin target. The velocities imparted to the atoms are selected so that when they emerge from the target they are sufficiently ionized to produce hyperfine fields large enough to cause observable rotations of the nuclear spin and corresponding perturbations of the γ-ray angular distribution of the excited state. An external magnetic field is applied along the orientation axis (i.e., the beam direction) and increased until the nuclear moments are decoupled from the hyperfine fields (i.e., the Larmor precession of each atomic moment becomes so rapid that the nuclear moment can no longer follow it). The decoupling process can be observed through the perturbation of the angular distribution, and its dependence on the external field (the "decoupling curve") is a sensitive measure of the product of the nuclear moment and the atomic hyperfine fields. At the present time, the precision of the method for measuring moments rests primarily on the accuracy with which the atomic fields can be determined. Fortunately, it is usually possible to produce ionization states by appropriate velocity selection in which a single atomic configuration dominates the hyperfine interaction. These configurations are usually unpaired s states for which fairly reliable calculations can be made. Moreover, as the decoupling field is increased, the weak fields decouple first and the strong fields later on so that, to some extent, the various hyperfine fields are treated separately. This partial separation of the decoupling fields improves the accuracy of the analysis.

The nuclear state of interest was populated via the ^{40}Ca(α, α')^{40}Ca* reaction with a beam of 16.17-MeV α particles from the Stanford tandem accelerator. The target was either a 200-μg/cm^2 deposit of natural Ca metal on a 5-μg/cm^2 backing of carbon for the decoupling measurements, or a similar deposit on a 3-mg/cm^2 backing of Au for a recoil-into-solid measurement to give the unperturbed angular distributions. After passing through the thin target, the beam was stopped several meters from the target to reduce background. The 3.737-MeV γ rays were detected in a 24-×24-cm NaI(Tl) detector located at 60° and 48 cm from the target and a 12.7-×15.2-cm NaI(Tl) detector at 150° and 28 cm from the target, both operated in coincidence with backscattered α particles detected in an annular surface-barrier detector for which the maximum off-axis angle was 6.7°. The coincidence circuit employed standard fast-slow coincidence requirements with a resolving time of 50 nsec. A superconducting magnet, mounted in the vacuum of the target chamber, produced longitudinal fields up to 38 kG at the target site, although the maximum value used in this experiment was 24 kG. Soft iron pipes and high saturation Si-Fe magnetic shields were placed around the detectors and the Dewar to reduce the effect of the field on the detector phototubes. An Al foil 215 μg/cm^2 thick was placed over the particle detector to reduce the influx of secondary electrons which the magnetic field tended to focus onto the detector. A special target-holder interlock assembly allowed the target to be changed without breaking vacuum while the Dewar remained cold and the superconducting magnet remained charged.

The angular correlation can be calculated for this reaction and, after allowance for corrections

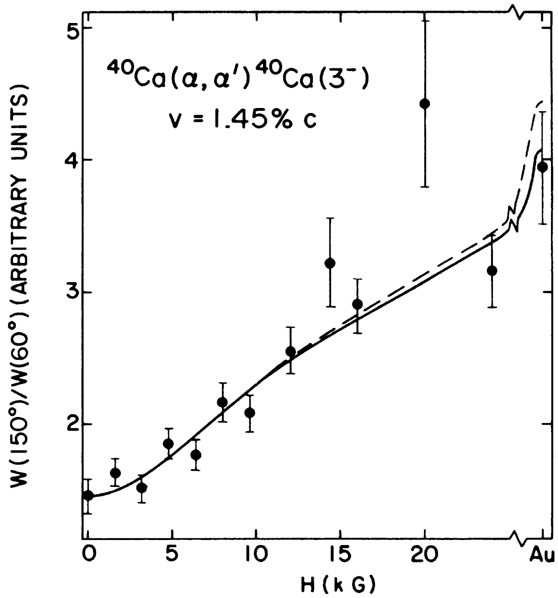

FIG. 1. Decoupling curve for the 3^-level of ^{40}Ca obtained from the $^{40}Ca(\alpha\alpha'\gamma)^{40}Ca$ reaction at a recoil velocity of 1.45%*c*. The curves are best fits obtained with the statistical model and 3*s*, 3*p*, and 4*s* fields as explained in the text. For the solid curve the fraction of ions experiencing perturbation is 82%; for the dashed curve the fraction is 89%. The point at the right-hand side labeled "Au" refers to recoil into a solid Au backing.

due to the finite size of the γ and particle detectors, is given by the angular correlation coefficients $A_2 = 0.991$, $A_4 = 0.264$, and $A_6 = -2.1281$. It was not possible to resolve the 3^- state of ^{40}Ca from the nearby 2^+ state at 3.904 MeV in either the particle or γ spectrum. However, higher-resolution spectra were obtained which indicated that the 2^+ peak was only about 10% of the 3^- peak and this "contamination" was taken into account in the analysis.

The atomic charge-state distribution was calculated from the expressions of Nikolaev and Dmitriev,[4] which for our recoil velocity of 1.45% of the speed of light, gives an average charge state of 5.8 and a width of 1.1 charges. The single-electron hyperfine field strengths were calculated in a Hartree-Fock-Slater (HFS) approximation with the program of Herman and Skillman.[5] A single 3*s* electron is found to give rise to a field of 18.8 MG, a $3p_{1/2}$ electron a field of 5.4 MG, and a 4*s* electron one of 7.7 MG. Russell-Saunders coupling was assumed and the procedure of Goudsmit[6] was used to calculate the field for each atomic term. The *K* and *L* shells were assumed to contain no vacancies and the remaining electrons were distributed statistically over the *M* and *N* shells and the 5*s* orbital, but appreciable perturbations were produced only by electrons in the 3*s*, 3*p*, and 4*s* orbitals. The very small contributions from 3*d* electrons were ignored. The fields were assumed to be static since, according to the compilation of Wiese, Smith, and Miles,[7] atomic transition rates are comparable to the nuclear lifetime only for the $4s \rightarrow 3p$ transition (which was taken into account in calculating the weight of the various atomic terms). The procedure of Steffen and Frauenfelder[8] was used to calculate the perturbation factors.

The angular correlation was "measured" by recording the ratio of α-γ coincidences at 150° to those at 60°, after correcting for the random coincidences. This ratio was then measured as a function of external field. The decoupling curve thus obtained is shown in Fig. 1. The point labeled Au is the value for recoil and implantation in a solid Au backing, for which no perturbation is expected. Thus, it corresponds to an "infinite" decoupling field. The curve shown is the best fit to the data. The parameters of the fit were the relative efficiency of the two detectors, the fraction of ions experiencing some perturbation, and the nuclear *g* factor. The atomic fields were taken from the HFS calculation. The fraction of ions experiencing perturbation, as determined from the fit, was $82 \pm 10\%$, which compares well with the value of 89% predicted by the model used. The value obtained for the *g* factor is $|g| = 0.56 \pm 0.13$, in agreement with the rough value of $g = +0.83 \pm 0.76$ obtained by Hensler *et al.*[9] in an implantation measurement. Taking the sign from that measurement, we adopt $g = +0.56 \pm 0.13$.

Although the error in this measurement is estimated to cover the uncertainties in the analysis, nevertheless the reliability of the measurement rests on the validity and accuracy of determining the contributions of the various hyperfine fields to the decoupling curve. The chief requirements are a knowledge of the charge-state distributions of the ions, the distributions of electrons over the vacant orbitals, and then accurate calculations of the hyperfine fields themselves. It is anticipated that our knowledge of these various quantities will improve as more measurements become available and the calculations are further refined. Already, measurements[2,3,10] on the 3^- level of ^{16}O with the present decoupling method have given values of the *g* factor in good agreement with the precise value obtained from hyperfine measurements on one-electron ^{16}O ions.[11]

From an extreme shell-model viewpoint we expect the 3^- state to be an $f_{7/2}$ particle coupled to a $d_{3/2}$ hole, with equal admixtures of proton and neutron configurations. This picture leads to a *g* factor of $+0.554$. Use of more realistic wave functions including three-particle–three-hole configurations gives a value of $+0.486$.[9] The collective model suggests a value of $+0.50$, and a theory of Simonov and Troitsky[12] pertaining to g factors of excited states of doubly-magic nuclei predicts the same value. The experimental value confirms the basic nature of this state, although it is not yet precise enough to establish the validity of any one theoretical refinement.

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