Nuclear g Factor of the First Excited State in V^{51}†

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The angular distribution of the resonance radiation from the 320-keV state in V^{51} has been measured using gaseous $Cr^{51}Cl_2O_2$ as the source of resonant gamma rays. The distribution can be described by $W(\theta)=1+(0.44\pm0.03)P_2(\cos\theta)$, corresponding to a mixing amplitude $\delta=+0.43\pm0.03$.

From the precession of the angular distribution pattern in a magnetic field perpendicular to the plane of scattering, a value $g=1.69\pm0.29$ was deduced for the g factor of the excited state, using $\tau=(2.5\pm0.2)\times10^{-10}$ sec for the mean life.

1. INTRODUCTION

THE properties of the lowest levels of V^{51}, which has a closed $N=28$ neutron shell, are determined by the three protons outside the closed $d_{3/2}$ shell. In the ground state the three $f_{7/2}$ protons couple in the usual way to give a total angular momentum $I=7/2$, in the first excited state they combine to $I=5/2$. The $M1$ transition between the two levels should be strictly forbidden by a simple selection rule,[1] if the two configurations were pure. Then the magnetic moment operator is proportional to the angular momentum and its matrix element vanishes because of the orthogonality of the two states. From the measured mean life of the first excited state,[2] $\tau=(2.5\pm0.2)\times10^{-10}$ sec (see[2–7] Table I), and the $E2$ transition rate calculated from the Coulomb excitation cross section,[8] one finds for the $M1$ transition probability a hindrance factor of 3×10^{-3}. This indicates that the states involved can be described by nearly pure $(f_{7/2}{}^3)_{7/2}$ and $(f_{7/2}{}^3)_{5/2}$ wave functions, and that therefore the g factors of both states should be close to the Schmidt limit for $f_{7/2}$ protons, $g_s=1.655$.

The g factor measured for the ground state of V^{51}, $g=1.471$,[9] is considerably lower than its Schmidt limit. Computations using configuration mixing[10] indicate that it is difficult to reconcile the low value of the magnetic moment with the low transition probability between the two levels. Since it was suggested that the V^{51} case with its relatively pure configurations might show whether the assumption of lower effective single-particle g factors is sufficient to account for the magnetic moments of the first few excited states belonging to the same configuration, a measurement of the magnetic moment of the 320-keV state appeared desirable. It was the purpose of the work presented in this paper to determine this quantity by observing the precession of the resonance radiation pattern in a magnetic field.[11]

TABLE I. Lifetime measurements of the 320-keV state in V^{51}.

Investigators	Method	Mean life (10^{-10} sec)
Schopper[a]	Resonance fluorescence, thermal method	1.9±0.6
Sunyar and Deutsch[b]	Delayed coincidences	2.8±0.3[g]
Nainan[c]	Delayed coincidences	4.0±0.6
Holland *et al.*[d]	Delayed coincidences	2.8±0.5
Frauenfelder *et al.*[e]	Resonance fluorescence, thermal method	2.7±0.5
Schwarzschild[f]	Delayed coincidences	2.5±0.2

[a] See reference 3.
[b] See reference 4.
[c] See reference 5.
[d] See reference 6.
[e] See reference 7.
[f] See reference 2.
[g] By mistake this value had been quoted as the half-life.

The 320-keV level in V^{51} is well suited for the application of the resonance fluorescence technique: The level is populated by electron capture from Cr^{51}, the neutrino recoil is sufficient to compensate for the gamma recoil energy losses as long as the mass of the recoiling system is kept low, the half-life of Cr^{51} is conveniently long (28 days), the abundance of V^{51} is high (99.75%), and the atomic number (23) is low. The main problem arises from the fact that, in order for the large recoil velocities to be preserved, the source material has to be kept in the gaseous phase.[12] With stable gaseous sources, the sensitivity of the method is sufficient to allow the determination of the g factor with an accuracy of a few percent. The present experi-

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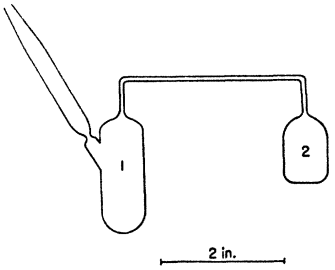

FIG. 1. Reaction vessel for the production of $CrCl_2O_2$.

ment did not realize this accuracy because the large gap electromagnet necessary for the measurements was available only for a limited time period.

2. PREPARATION OF SOURCES EMITTING RESONANT GAMMA RAYS

$CrCl_2O_2$ was chosen as the gaseous source material because of its high volatility at reasonably low temperatures and because it was known from previous experiments[3,13] that it yields, in spite of its high molecular weight, a resonance effect which is not much smaller than that expected for monatomic chromium vapor. A solution of $CrCl_3$ in HCl, containing 250 μg of Cr, obtained from Oak Ridge with a specific activity of up to 850 C/g, was evaporated to dryness in part 1 of the Pyrex reaction vessel (Fig. 1). After reaching a vacuum of 3×10^{-2} mm Hg, the ampoule was filled with 0.9 atm of Cl_2 and sealed. By heating part 1 of the vessel to 400°C for 30 min, $CrCl_2O_2$ was formed with a yield of more than 90%. The radioactive gas and the Cl_2 were then condensed in part 2 of the system by cooling with liquid nitrogen. The system was allowed to warm up slowly; Cl_2, evaporating first, passed through the capillary into part 1, whereas most of the $CrCl_2O_2$ was left in part 2. At this stage the capillary was sealed, separating the two parts. Ampoule 2, the final source container, was sealed close to its neck, while its bottom was cooled with liquid nitrogen again.

The radioactive $CrCl_2O_2$ was stable in the dark for several days, but decomposed rapidly upon exposure to light, leaving a brown deposit on the walls of the glass container. $CrCl_2O_2$ could be formed again by heating the ampoule to 400°C, if the original concentration of $CrCl_2O_2$ did not exceed 60 μg of Cr/cm^3. With 100 μg of Cr/cm^3, a black deposit was formed instead, insoluble in all common solvents.

Since slow decomposition took place in the dark as well, the $CrCl_2O_2$ sources were kept at 430°C for the resonance measurements, and a chromium concentration of less than 60 μg/cm^3 was used. Under these conditions the resonance counting rate decayed with the half-life of Cr^{51}, which proves that the sources were chemically stable over periods of several weeks. For some calibration measurements requiring a solid source, the ampoule was exposed to ultraviolet light, which decomposed the $CrCl_2O_2$.

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3. ANGULAR DISTRIBUTION OF THE RESONANCE RADIATION

It is well known that the angular distribution $W(\theta)$ of the scattered radiation for a sequence of angular momenta 7/2−5/2−7/2 can be represented by

$$W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta), \qquad (1)$$

the coefficients A_2 and A_4 depending upon the sign and magnitude of the $E2/M1$ mixing amplitude δ. From Coulomb excitation measurements[8] a partial lifetime $\tau_{E2}=1.38\times10^{-9}$ sec for the $E2$ transition can be deduced, which, combined with the lifetime of the level measured by delayed coincidences, $\tau=2.5\times10^{-10}$ sec, yields an absolute value of the mixing amplitude $|\delta|=0.47$. Since, for $|\delta|<1$, A_4 is so small that it can be practically neglected, a single parameter A_2 had to be determined by the measurement.

To avoid distortions of the angular distribution by crystalline fields, metallic vanadium was chosen as the material of the scatterer. The cubic structure of the metal excludes electrical field gradients at the position of the nuclei, and the paramagnetism of the conduction electrons should not affect the distribution.

A cylindrically symmetrical arrangement (Fig. 2) was used for the measurements. The accepted scattering angle could be changed by varying the relative positions of scatterer, source, and NaI detector. Data were taken for scattering angles of 106, 126, 136, and 143 deg. The probability of detecting resonance radiation with each arrangement was calculated, taking into account

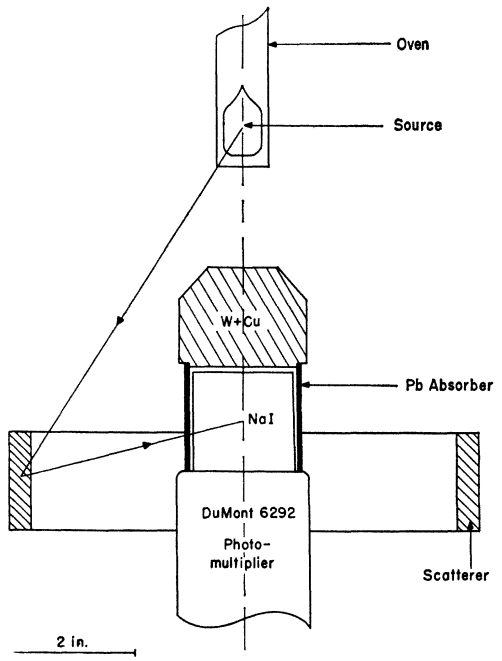

FIG. 2. Experimental arrangement used for measuring the angular distribution of the resonance radiation. The scattering angle could be varied by changing the relative positions of source, scatterer, and detector.

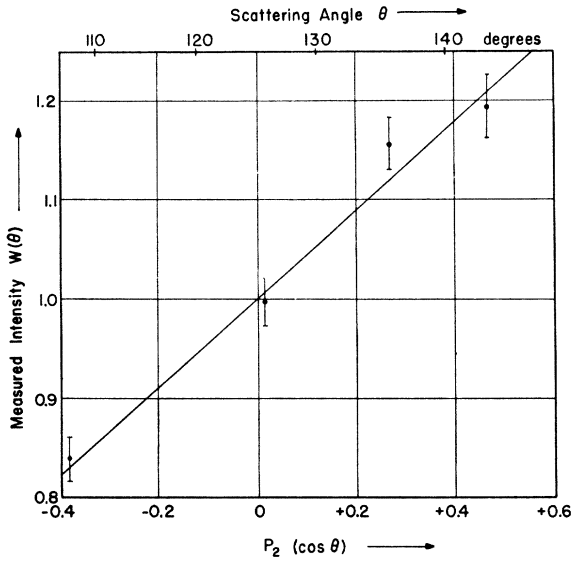

FIG. 3. Experimental values for the angular distribution of the resonance radiation. The curve represents a least square fit of $W(\theta)=1+A_2P_2(\cos\theta)$ to the measured points.

the solid angle subtended by the scatterer subdivisions at the position of the source, the attenuation of the incident and scattered radiation by the material of the scatterer and its container, and the probability of detecting a scattered quantum, measured with a Cr^{51} point source. A correction due to the finite size of the detector was applied to the mean value of $\cos^2\theta$. The scatterer, consisting of vanadium powder of 99.8% purity, was checked for uniformity by measuring the absorption of 145-keV gamma rays. Runs were taken alternately with a titanium comparison scatterer, which had been matched with the vanadium scatterer with respect to the electronic scattering. A least-square fit to the measured distribution of the resonance radiation (Fig. 3) yielded $A_2=0.45\pm0.04$.

A second set of data was obtained for scattering angles of 109 and 139 deg with a scatterer of dimensions similar to those of the vanadium powder scatterer, but consisting of several layers of vanadium metal sheet of 99.9% purity. A value $A_2=0.41\pm0.06$ was deduced from the measured intensity ratio. The weighted average of the two measurements is

$$A_2=0.44\pm0.03$$

corresponding to a mixing amplitude

$$\delta=+0.43\pm0.03.$$

This result is in agreement with the absolute value of δ calculated earlier from the comparison of the Coulomb excitation cross section with the delayed coincidence lifetime, and with a recently published value[14] $\delta=+0.52\pm0.07$.

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4. PRECESSION IN A MAGNETIC FIELD

The effect of a magnetic field H, applied to the scatterer at right angles to the plane of scattering, can be described by the well-known precession of the angular distribution pattern around the field direction with the Larmor frequency ω of the excited state. Averaged over the lifetime of the level, the distribution in the presence of a field H is given by

$$W(\theta,H)=\int_0^\infty W(\theta-\omega t,0)e^{-t/\tau}dt \Big/ \int_0^\infty e^{-t/\tau}dt, \quad (2)$$

where τ is the mean lifetime of the level and $W(\theta,0)$ the zero-field distribution.

For $\omega\tau\ll1$, which applies to the present experiment, the effect of the field is given with sufficient accuracy by a rotation of the zero-field distribution by an angle

$$\Delta\phi=\omega\tau. \quad (3)$$

The precession angle $\Delta\phi$ was determined from the ratio of two resonance counting rates taken at a given angle with opposite directions of a strong magnetic field. With the measured angular distribution and the experimental geometry (Fig. 4), an intensity change of 1.01% was expected for a rotation by one degree.

A plane geometry (Fig. 4) was used for the magnetic measurements. The scatterer, a piece of solid vanadium of 99% purity, $2\frac{1}{2}$ in.$\times1\frac{1}{2}$ in.$\times\frac{1}{2}$ in., was placed between the pole pieces of an electromagnet capable of producing

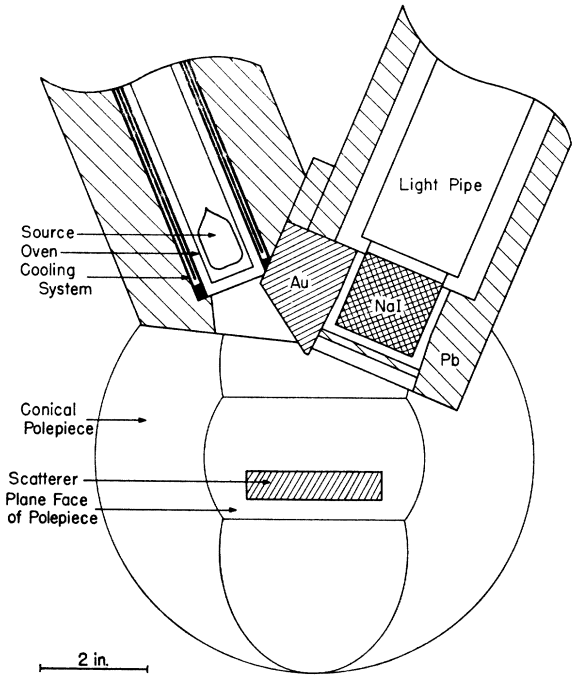

FIG. 4. Experimental arrangement for the precession experiment. The direction of the magnetic field, which was perpendicular to the plane of the drawing, could be reversed.

a field strength of 25 000 G with a gap of 2 in. The photomultiplier tube was removed from the region of high field strength by using a light pipe one foot long, and was shielded with eight layers of high permeability material in an arrangement similar to that used by Bodenstedt *et al.*[15] In spite of the shielding, a change in amplification of 0.27% upon field reversal was observed. Due to this effect a correction had to be applied to the resonance counting rate amounting to (5±5)% of the intensity change due to the precession of the angular distribution. The effect of the magnetic field on the electronic part of the scattering from the vanadium and on scattering from the polepieces, which formed the bulk of the background, was taken into account by alternating measurements with the vanadium scatterer and with a comparison scatterer consisting of Ti and Cu. Runs of 10-min duration were taken with each field direction and each scatterer. A small correction due to imperfect matching of the scatterers was obtained from measurements with a solid source, which gave rise to electronic scattering only.

The measured change of the resonance counting rate due to reversing a field of 24 700 G was (5.81±0.80)%, corresponding to a precession of $\Delta\phi=(2.88\pm0.44)$ deg in each direction.

5. g FACTOR OF THE 320-keV STATE

From the measured precession angle $\Delta\phi=2.88$ deg, Eq. (3), and the relation

$$\omega=gH_V\mu_{nm}/\hbar, \tag{4}$$

the nuclear g factor can be obtained, if the magnetic field H_V at the position of the vanadium nucleus is known. Measurements of the Knight shift[16] indicate that, due to the paramagnetism of the conduction electrons, the internal field is 0.6% higher than the external one. With $\mu_{nm}=5.05\times10^{-24}$ erg G^{-1} for the nuclear magneton, $\hbar=1.05\times10^{-27}$ erg sec, and $\tau=2.5\times10^{-10}$ sec for the mean lifetime of the 320-keV state,

$$g=+1.69\pm0.29$$

was obtained, corresponding to a magnetic moment of

$$\mu=+(4.2\pm0.7)\mu_{nm}.$$

Theoretical estimates[17] of the g factor for the $5/2^-$ state in V^{51} indicate that it should be close to the Schmidt limit for $f_{7/2}$ protons, $g_s=1.655$. Within the limits of error the g factor obtained in this experiment is in agreement with this value.

Because of the unexplained deviation of the V^{51} ground-state magnetic moment from the Schmidt limit and the possibly general consequences of the case, it would be highly desirable to measure the g factor of the 320-keV state more accurately than it was possible in this work. Considering the fact that the magnetic moment information reported here was obtained in 160 h of counting with a source of about 150 mC of Cr^{51} and that the errors are mainly statistical, it should be possible to achieve an accuracy of 5% with a more extended experiment, using the method described above.

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