one retains higher order terms one will not necessarily predict exactly $P=-v/c$ for first-forbidden transitions.[3,28] Kotani and Ross[28] have shown for RaE that if one assumes invariance under time reversal, the expression for longitudinal polarization reduces to $P_L \cong -(p/W)(R_2/C)$, where p and W are the momentum and total energy of the electron, C is the spectrum shape factor, and R_2 is dependent only on nuclear parameters and is not a function of electron energy. Since the ratio of nuclear matrix elements cannot be determined exactly from the energy spectrum shape, the value of R_2 is uncertain. Kotani and Ross consider that a low value of R_2 may reasonably be expected for RaE but they have not made quantitative estimates as yet.[29] In a recent communication Bincer, Church, and Weneser[30] have calculated the degree of polarization expected for beta rays of RaE using Plassmann and Langer's[31] best fit to the spectrum shape. Their predictions show that the polarization is a function of the beta-ray energy for a given fit and that the absolute value depends on the choice of fit. The average value expected in our apparatus from the mean of their predicted range of values is $\sim -0.6v/c$ in agreement with our experiment. A detailed study of the polarization of RaE beta rays as a function of v/c would prove valuable in establishing the nuclear parameters for this interesting nuclide.

VIII. CONCLUSION

The experiments reported here on P^{32}, Y^{90}, Pr^{144}, and Au^{198} give results which are consistent with the current view that the longitudinal polarization of negative beta rays is $-v/c$. The RaE experiments, however, indicate a polarization magnitude of less than v/c. Interference between the Fermi and Gamow-Teller contributions is believed to account for the large ft value and the nonallowed shape of the RaE beta spectrum; such interference may also give rise to low polarization.

Note added in proof.—Low values for the longitudinal polarization of RaE β rays have recently been reported by two other groups. W. Bühring and J. Heintze [Phys. Rev. Letters 1, 176 (1958)] compared the longitudinal polarization of 250–600 kev β rays from Tl^{204}, Y^{91}, and RaE using the technique of multiple followed by Mott scattering. They find that $\langle P/(-v/c)\rangle$ for RaE in this energy range is 0.83 ± 0.02. Wegener, Bienlein, and Issendorff (preprint) have measured the polarization of the RaE β rays using a spherical electrostatic analyzer and Mott scattering. For β energies of 120, 155, 209, and 290 kev their measured longitudinal polarizations are $P/(-v/c)=0.69\pm0.04$, 0.75 ± 0.04, 0.75 ± 0.03, and 0.66 ± 0.06, respectively.

IX. ACKNOWLEDGMENTS

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Excited States of V^{51} and Cr^{53}†

M. Mazari,* W. W. Buechner, and A. Sperduto
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

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The region of excitation in V^{51} up to 4.12 Mev has been investigated through studies of the inelastic scattering of protons. In this region of excitation, thirty-five excited states were found. The low-lying excited states of Cr^{53} were investigated through the $Cr^{52}(d,p)Cr^{53}$ and the $Mn^{55}(d,\alpha)Cr^{53}$ reactions. The ground-state Q values for these reactions are 5.720 ± 0.006 and 8.275 ± 0.008 Mev, respectively. The first two excited states in Cr^{53} are at 0.565 and 1.008 Mev. In these studies, the bombarding beam was provided by an electrostatic accelerator, and the reaction products were analyzed with a broad-range magnetic spectrograph.

EXCITED STATES OF V^{51}

In a previous paper,[1] we reported on studies of the inelastic scattering of protons from vanadium and remarked that, in the region of excitation above the fourth excited state at 1.819 Mev, the level scheme was of considerable complexity. We have recently reinvestigated this reaction under somewhat better conditions than in the previous work.

A 6.51-Mev proton beam from the MIT-ONR accelerator was used, and the scattered particles were analyzed with the broad-range magnetic spectrograph at an angle of 130 degree with respect to the beam.

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* Now at the National University of Mexico.

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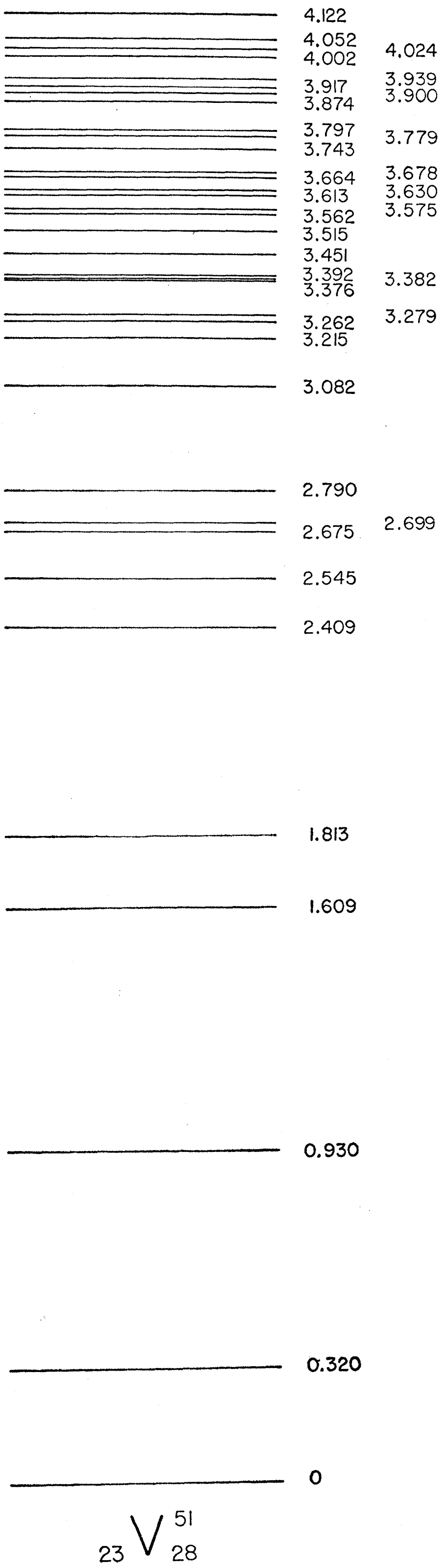

FIG. 1. Energy-level diagram for V^{51}.

TABLE I. Energy levels of V^{51} from the $V^{51}(p,p')V^{51}$ reaction.

Level	Excitation energy (Mev)	Level	Excitation energy (Mev)
1	0.320±0.004	19	3.562±0.008
2	0.930±0.004	20	3.575±0.008
3	1.609±0.004	21[a]	3.613±0.008
4	1.813±0.008	22	3.630±0.008
5	2.409±0.008	23	3.664±0.008
6	2.545±0.008	24	3.678±0.008
7	2.675±0.008	25[a]	3.743±0.008
8	2.699±0.008	26	3.779±0.008
9	2.790±0.008	27[a]	3.797±0.008
10	3.082±0.008	28	3.874±0.008
11	3.215±0.008	29	3.900±0.008
12	3.262±0.008	30	3.917±0.008
13	3.279±0.008	31	3.939±0.008
14	3.376±0.008	32	4.002±0.008
15	3.382±0.008	33	4.024±0.008
16	3.392±0.008	34	4.052±0.008
17	3.451±0.008	35	4.122±0.008
18	3.515±0.008		

[a] Probable double levels.

These new data, together with those presented in reference 1, lead to the values listed in Table I for the excited states of V^{51} between the ground state and 4.12 Mev.

In the previous work, values were given for the first four excited states, and these are in excellent agreement with the values presented here. An energy-level diagram for V^{51} based on the present results is shown in Fig. 1.

EXCITED STATES OF Cr^{53}

The low-lying excited states of Cr^{53} have been investigated with the $Mn^{55}(d,\alpha)Cr^{53}$ and the $Cr^{52}(d,p)Cr^{53}$ reactions. This work was carried out primarily as a part of a study of the ground-state Q values for these two reactions. In the case of the (d,α) reaction, the measurements were made with a bombarding energy of 6.54 Mev and an angle of observation of 50 degrees. The ground-state Q value was found to be 8.275±0.008 Mev, and alpha-particle groups were found corresponding to excited states in Cr^{53} at 0.562 and 1.008 Mev. In the case of the (d,p) reaction, a natural chromium target was employed with a bombarding energy of 6.54 Mev and an angle of observation of 130 degrees. A large number of proton groups were observed, and those associated with the formation of Cr^{53} were identified on the basis of the correspondence of the calculated excitation energies with those determined from the studies of the $Mn^{55}(d,\alpha)$ reaction. In this way, the ground-state Q value was found to be 5.720±0.006 Mev, and excited states in Cr^{53} were established at 0.565 and 1.008 Mev. An additional intense proton group was observed and is also assigned to the $Cr^{52}(d,p)Cr^{53}$ reaction on the basis of its yield compared with the other observed groups. The corresponding excitation energy in Cr^{53} is 2.325 Mev. It was not possible to check this assignment through the

$Mn^{55}(d,\alpha)Cr^{53}$ studies, since the corresponding region of the alpha-particle spectrum was obscured by groups from contaminants.

While the good agreement between the values for the excited states in Cr^{53} obtained from the $Mn^{55}(d,\alpha)$ and $Cr^{52}(d,p)$ reactions provides a check on the correct assignment of the ground-state groups of these reactions, additional confirmation is obtained by comparing the Q value for the $Mn^{55}(p,\alpha)Cr^{52}$ reaction calculated from the results reported here with that observed experimentally.[2] This latter value is 2.568±0.008 Mev and is in agreement with the calculated one within the experimental errors. The present results on Cr^{53} are in substantial agreement with those reported by other workers.[3,4]

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Steady-State Free Precession in Nuclear Magnetic Resonance*

H. Y. Carr
Department of Physics, Rutgers University, New Brunswick, New Jersey

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A steady-state free precession technique for observing nuclear magnetic resonance is described. A mathematical analysis is presented for certain special conditions, and initial experiments verifying the results of this analysis are reported. This technique provides two opportunities for improving the signal-to-noise ratio. First, it provides a mechanism, similar to that of the "spin echo," for eliminating the effect of the inhomogeneity of the magnetic field on signal strength. This permits the effective use of larger samples. In the second place it provides a steady-state signal which can be observed with a narrow-band detector. Under certain conditions the technique has a broad response as a function of frequency or field. The upper limit to the width of this response is determined by the electronic apparatus supplying the rf pulses rather than the magnet or the nuclear sample.

I. INTRODUCTION

NUCLEAR magnetic resonance in condensed matter was first observed by Purcell, Torrey, and Pound[1] and by Bloch, Hansen, and Packard.[2] The experimental techniques used by these two groups[3,4] provide an output signal which can be related to the forced precession of a steady-state nuclear magnetic moment associated with the bulk sample. The precession is called forced because at the time the output signal is observed, the precession is determined not simply by the static magnetic field but also to a large extent by an additional component of the field oscillating near the resonance frequency. The net nuclear moment is considered in a steady-state because in periods of time equal to or shorter than the spin relaxation times it does not undergo changes in amplitude comparable to its maximum amplitude.

Torrey[5] in subsequent experiments introduced a transient forced precession technique. Although he also observed his output signal while the oscillating component of the external field was being applied, he was primarily interested in the transient growth of the nuclear moment at the beginning of a pulse of the oscillating field. The "rapid passage" method introduced by the Bloch group[4] may also be considered a transient forced precession technique.

By pursuing a suggestion which had been made by Bloch,[6] Hahn[7] successfully observed a transient signal or "tail" following the removal of an intense pulse of the oscillating magnetic field. Later, using essentially the same technique, Hahn[8] discovered and explained the "spin echo" effect. Since both "tails" and "echoes" occur when the oscillating field is removed, this is a free precession technique. Furthermore, it is a transient technique since the net nuclear moment undergoes large changes in amplitude. The transient "wiggles" effect[3] may be considered a mixture of free and forced precession.

It is the purpose of this paper to describe an experiment using a steady-state free precession technique and to indicate its special properties. The experimental apparatus used in this experiment is identical to that of the conventional transient free precession equipment with one exception. It is essential that the oscillating rf field be phase coherent from pulse to pulse.

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