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Inelastic Proton Scattering from Vanadium*

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The low-lying excited states of V^{51} have been investigated by means of inelastic proton scattering. Protons were accelerated to 6.0, 7.0, and 7.4 Mev in the MIT-ONR electrostatic generator, and the scattered protons were analyzed with a broad-range magnetic spectrograph, observations being made at 90 and 130 degrees to the incident beam. Proton groups were found which corresponded with levels in V^{51} at 0.322 ± 0.002, 0.931 ± 0.003, 1.614 ± 0.005, and 1.819 ± 0.05 Mev. A large number of lower energy groups were observed, which are associated with excited states between 1.85 and 4.50 Mev. Two groups of alpha particles were also observed and assigned to the ground state and first excited state formed in the $V^{51}(p,\alpha)Ti^{48}$ reaction ($Q=1.161$ and 0.167 Mev).

I. INTRODUCTION

INFORMATION about the excited states of V^{51} has been obtained previously from the beta decay of Ti^{51} and Cr^{51} and from inelastic scattering by V^{51}. The data on the beta-decay energy of Ti^{51} are in poor agreement, but all observers agree on the existence of a 0.323-Mev gamma ray.[1] In addition, Bunker and Starner[2] and Jordan *et al.*[3] have observed 0.928- and 0.605-Mev gamma rays, the latter in coincidence with the 0.323-Mev radiation, while Nussbaum[4] reports a 0.935-Mev gamma ray. The 0.323-Mev gamma ray is also found from the electron capture[1,2] of Cr^{51}, and some authors[5,6] have reported one of lower energy, which they ascribed to a level in V^{51} at 0.237 or 0.267 Mev.

From inelastic proton scattering, Hausman *et al.*[7] reported levels in V^{51} at 0.32, 0.48, 1.16, and 1.84 Mev, and at higher energies. This work was carried out with 8-Mev protons, and, except for the first state, these results do not agree with the beta-decay data. The 0.323-Mev level has been observed in experiments on Coulomb excitation by alpha particles.[8] In addition, in this work a 0.880-Mev gamma ray was tentatively ascribed to a level in vanadium. Also, gamma rays with energies of 0.33, 0.97, and 1.67 Mev have been reported to result from the bombardment of vanadium with 3.2-Mev neutrons.[9]

The spin of ${}_{23}V_{28}{}^{51}$ has been measured[10]; it is 7/2, in accordance with the shell model which predicts that it has filled neutron shells and 3 protons in the $f_{7/2}$ shell.[11] The energies of the states of the $(f_{7/2})^3$ configuration have been calculated theoretically,[12–14] and it is predicted that, with a $7/2^-$ ground state, the first two excited states should be $5/2^-$ and $3/2^-$. Furthermore, the first single-particle level should be $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$. The best cases in which to look for the $(f_{7/2})^3$ or $(f_{7/2})^{-3}$ multiplet are Ca^{43} or Ca^{45}, with 20 protons in closed shells and 3 or 5 $f_{7/2}$ neutrons, and V^{51} or Mn^{53}, with 3 or 5 $f_{7/2}$ protons and 28 neutrons in closed shells. We are presently engaged in a study of the $Ca^{42}(d,p)Ca^{43}$ and $Ca^{44}(d,p)Ca^{45}$ reactions[15] and have found it interesting to compare the V^{51} spectrum with the spectra of Ca^{43} and Ca^{45}. Moreover, it was pointed out[16] to us that the existing experimental data did not agree with theory. If the lowest levels reported by Hausman *et al.* were to be interpreted as members of the $(f_{7/2})^3$ multiplet, it would be surprising not to see the 0.48-Mev level appear in the decay of Ti^{51}, which, according to the shell model, should have a $3/2^-$ ground state. For these reasons, we have investigated the $V^{51}(p,p')V^{51*}$ reaction with the MIT–ONR electrostatic generator and the broad-range magnetic spectrograph.

II. EXPERIMENTAL METHOD

A thin target of vanadium evaporated onto a formvar film was used for this work. It was prepared by Schwager and Cox[17] and had been used in an investigation of the $V^{51}(d,p)V^{52}$ reaction.[18] This target was bombarded with protons from the ONR electrostatic accelerator,[19] and the protons emitted were analyzed

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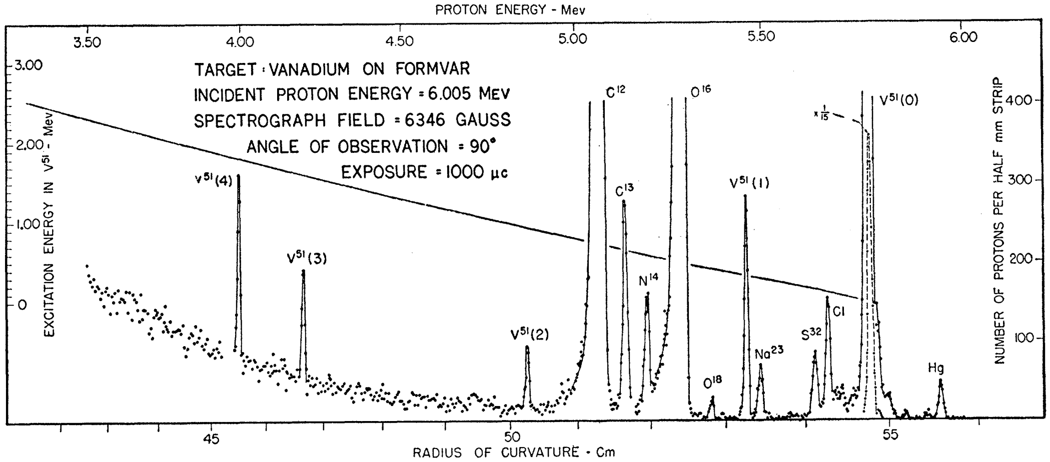

FIG. 1. Proton groups from vanadium target. Incident proton energy = 6 Mev, $\theta = 90°$.

in momentum with a broad-range magnetic spectrograph.[20]

A feature of this spectrograph is that a considerable portion of the entire spectrum is recorded simultaneously. The data in Fig. 1, for example, were recorded with a single exposure of 1000 microcoulombs. In this case, the bombarding energy was 6.005 Mev, and the angle of observation was 90 degrees. In addition to proton groups elastically scattered from the various nuclei in the target, several groups are evident which are due to inelastic collisions. A sensitive method for determining the mass of the nuclei from which the groups originate consists in making observations at other angles and bombarding energies. In the present case, such additional exposures were made at 90 degrees with bombarding energies of 7.040 and 7.420 and at 130 degrees with 7.420 Mev. The data from the latter exposure are shown in Fig. 2. These various exposures were made over a considerable time interval, and during the period when the exposure for Fig. 1 was made scattering from various slit edges gave rise to the low-energy background visible in this figure. This situation was considerably improved by the time of the exposure of Fig. 2, and additional changes have still further reduced this background, as is evident in Fig. 3, which was recently made to investigate the lower energy groups from the reaction.

III. RESULTS

From the results of calculations based on the observed energies of the groups at the various bombarding energies and observation angles, the assignments indicated on Figs. 1 and 2 have been made. In addition to those arising from various contaminants, five groups which originate from the vanadium are evident, the highest energy, most intense group corresponding to the ground state and the four (Nos. 1 through 4) of lower energy corresponding to excited states in V^{51}. The excitation energies calculated from these groups are 0.322 ± 0.002, 0.931 ± 0.003, 1.614 ± 0.005, and 1.819 ± 0.005 Mev. These values are the averages of those obtained from the 90-degree observations at 6- and 7.4-Mev incident energy and from the 130-degree data taken with 7.4-Mev protons. In each case, the

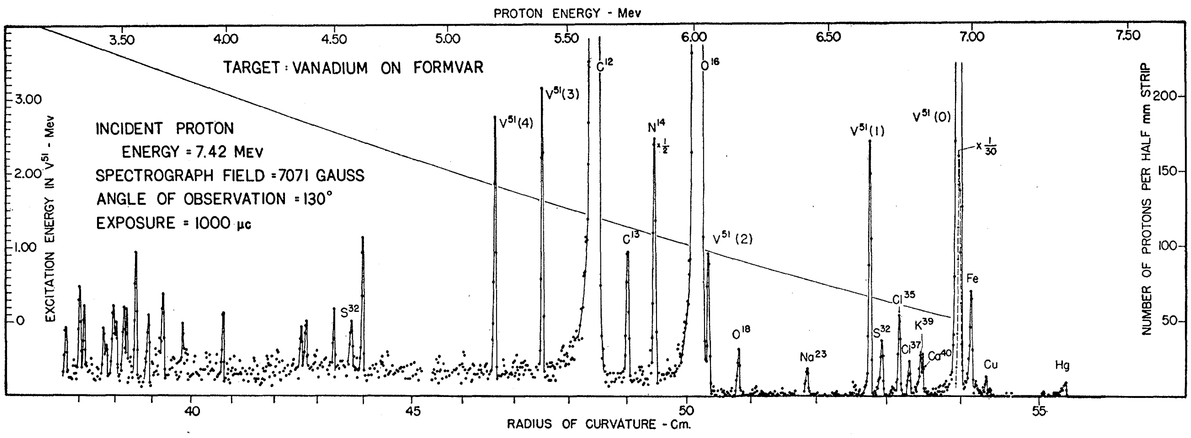

FIG. 2. Proton groups from vanadium target. Incident proton energy = 7.4 Mev, $\theta = 130°$.

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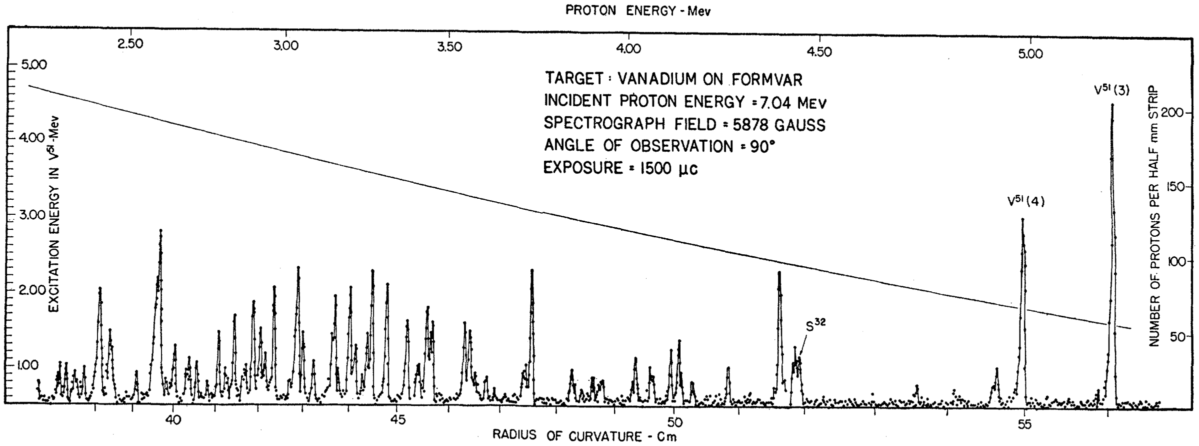

FIG. 3. Low-energy proton groups from vanadium target. Incident proton energy = 7.0 Mev, $\theta = 90°$.

individual results agreed with the average values within one kilovolt. In the calculation of the excitation energies, since the results depend on the energy differences between groups recorded on the same plate, systematic error tend to cancel out, and the results are essentially unaffected by the uncertainties in the incident proton energy. The first two of these states have energies which are in good agreement with those inferred from recent gamma-ray measurements,[2,3] and the first three agree within the errors with the gamma-ray energies found from neutron inelastic scattering.[9]

In each figure, a curve is drawn which gives the excitation energy in V^{51} as a function of peak location. It can be seen that in Fig. 1, the region between 0.5 and 0.9 Mev in V^{51} is to a large extent obscured by the intense groups from carbon, nitrogen, and oxygen, but that the region between the second and third levels in vanadium is relatively free of background. The settings for the exposure of Fig. 2 were such that the intense contaminant groups came between the second and third vanadium groups, so that the region between the first and second groups (0.3- to 0.9-Mev excitation in V^{51}) was quite free of background in this case.

In this way, we have made a study of those regions where other excited states of V^{51} have been reported. There is no evidence in this work for levels below 0.32 Mev. Except for the level at 0.32 Mev, the present results disagree with those previously obtained[7] from inelastic proton scattering from vanadium. While the reported level at 1.84 Mev probably corresponds with that measured here as 1.81 Mev, the 0.93- and 1.61-Mev states found in the present work were not reported in the earlier investigation, and we find no evidence for states at 0.48 and 1.16 Mev.

Also visible in Fig. 2 are a considerable number of lower energy proton groups. In order to investigate this region, the exposure of Fig. 3 was made. In this case, the spectrograph field was such that the groups associated with the 1.6- and 1.8-Mev levels in V^{51} appeared at the high-energy end of the plate. Because of the reduction in the background between the times of the exposures for Figs. 2 and 3, the latter shows a number of additional groups in the region of excitation common to the two. Except for the group indicated as arising from an excited state in sulfur ($Q = -2.23$ Mev), all the low-energy groups in Fig. 2 can be identified with various intense groups in Fig. 3, and their energies depend on angle of observation and incident energy in the manner expected for groups from vanadium. From the preliminary results of concurrent work on inelastic scattering from the various contaminant nuclei, it can be said that all the groups in Fig. 3 with a peak height greater than 25 protons per strip are associated with vanadium. However, some of the weaker groups arise from these contaminants, and it is worth emphasizing the importance of target cleanliness in work of this sort. Even for nuclei as heavy as iron, the inelastic groups have intensities that are a fair fraction of the elastically scattered group.

A group attributed to $Fe^{56}(p,p')Fe^{56}$ (0.845-Mev level) has been observed at these energies and angles from other targets with an intensity of about 25% of the ground-state group. In the figures shown, this group would be obscured by the carbon elastic group in Fig. 1 and is coincident with the O^{18} elastic group in Fig. 2. Except for the carbon, oxygen, and sulfur, which occur in the Formvar, and for the iron which is a contaminant of the vanadium used, the other nuclei indicated in Fig. 2 appeared on the target as a result of the method of preparation. These other contaminants can be eliminated by the preparation of the targets in a dust-free atmosphere and the use of distilled water and carefully purified reagents.

It is clear that, in the region of excitation above 2.4 Mev, the levels of V^{51} are of considerable complexity. Many of the groups in Fig. 3 consist of more than one component, the resolution in the present work being limited by the target thickness. This region could be studied in more detail using thinner targets and lower field strengths. However, at the present time, such a detailed study does not appear worth while.

Although the settings for the various exposures were determined by the proton spectra under investigation, on three of the plates an alpha-particle group was observed which, from its shift in energy, has been assigned to the $V^{51}(p,\alpha)Ti^{48}$ reaction. The Q-value for this group is 0.167 ± 0.010 Mev. On one of the exposures, a higher energy alpha group was also observed. This group was not recorded at the other energies and angles, as was to be expected if it also is from the $V(p,\alpha)$ reaction. On this assumption, its Q-value is 1.161 ± 0.010 Mev. While the masses in this region are not known to a sufficient accuracy to determine whether this is the ground-state group, it seems probable that this is the case and that the other group is from the first excited state of Ti^{48}. The energy of this state, as determined from measurements on the decays of Sc^{48} and V^{48}, is 0.990 Mev[1,21] in good agreement with the value obtained by taking the difference between the Q-values.

It is a pleasure to acknowledge our continued indebtedness to Mr. Wilton A. Tripp for the measurements on the nuclear track plates and to our colleagues for much helpful assistance.

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Nuclear Levels of Lu^{175}[†][*]

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The negatron decay of Yb^{175} (4.2 day) and orbital electron capture decay of Hf^{175} (70 day) to Lu^{175} have been investigated in detail using a magnetic lens spectrometer, 180° permanent magnet spectrographs, scintillation spectrometers, and coincidence techniques. Eleven gamma transitions in Lu^{175} of the following energies and indicated multipolarities have been observed: 89.3 ($M1+E2$), 113.6 ($M1+E2$), 137.6, 144, 229.3 ($E2$), 251, 282.4 ($E1+M2$), 318.6, 342.9 ($M1+E2$), 396.0 ($E1+M2$), and 432.2 kev. On the basis of these measurements, consistent decay schemes for Yb^{175} and Hf^{175} are proposed. Observed nuclear levels in Lu^{175} excited by the radioactive decay of these two nuclides occur at 113.6, 251.2, 342.9, 396.0, and 432.2 kev and are assigned spin and parity values $9/2+$, $11/2+$, $5/2+$, $9/2-$, and $5/2+$, respectively. The levels at 113.6 kev and 251.2 kev constitute a rotational band whose base state occurs at stable Lu^{175} ($7/2+$).

I. INTRODUCTION

Lutecium-175, daughter nucleus of Yb^{175} and Hf^{175}, has a measured ground-state spin of 7/2.[1] According to the formulation for collective rotational motion in highly deformed nuclei,[2] Lu^{175} should thus be expected to exhibit a well-developed rotational structure, and, indeed, what appear to be rotational levels have recently been observed in this nuclide by means of Coulomb excitation.[3] It therefore becomes of interest to apply nuclear spectroscopy techniques, i.e., study of the radiations of Yb^{175} (4.2 day), and Hf^{175} (70 day) to investigate in greater detail, if possible, the characteristics of the rotational transitions in Lu^{175}. In addition there exist features in the previously studied decay schemes of Yb^{175} and Hf^{175} which demand further clarification.[4] Therefore, a detailed reinvestigation of the radioactive decay of these two nuclides has been performed.[5]

II. DECAY OF Yb^{175}

(a) Source Preparation

Yb^{175} was prepared by thermal neutron bombardment of Yb_2O_3 [6] of natural isotopic abundance. Fractions of Yb^{169} (32-day) and Yb^{177} (1.8-hr) were also activated in the irradiation. All studies reported herein were performed after the Yb^{177} had essentially decayed to Lu^{177} (6.8-day). The quantity of Lu^{177} thus activated was found to be innocuous as far as the study of the Yb^{175} decay was concerned. The gamma activity accompanying the decay of the orbital electron capture isotope Yb^{169}, however, had to be carefully taken into account throughout the Yb^{175} experiments. Fortunately the relatively long half-life of Yb^{169} as compared to that of Yb^{175} enabled an unambiguous separation of the emanations of the two isotopes to be realized.

(b) Gamma-Ray Experiments

The results of a study of the gamma-ray spectrum engendered by the radioactivity produced through thermal neutron bombardment of Yb_2O_3 is shown in Fig. 1. The spectrum was obtained with a $1\frac{1}{2}\times1\frac{1}{2}$ inch NaI(Tl) crystal mounted on a Du Mont 6292 photomultiplier tube. A ten-channel analyzer was used for

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[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

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