volved in the calculation reveals that while they are large, they could not, without the greatest difficulty, be stretched to explain so large a discrepancy.[9a]

A similar calculation on the data from references 3 and 4 indicates that, if a dineutron were stable,[10]

$$\text{for bismuth, } \sigma(\delta,\gamma) \lesssim 10^{-29}\ \text{cm}^2;$$

$$\text{for helium, } \sigma(\delta,\gamma) \lesssim 5\times 10^{-28}\ \text{cm}^2.$$

Since (δ,γ) reactions compete with (δ,n) reactions in which neutron emission is energetically possible by at least 7 Mev, these cross sections are not unreasonably small. In addition, there is greater uncertainty in the application of the statistical theory of nuclear reactions to fission than to simpler reactions such as (p,δ). By use of (δ,p) detection, the sensitivity of the search for the dineutron in fission could be extended to almost any desired sensitivity by using a sufficiently large quantity of copper.

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[9a] *Note added in proof:*—It has recently been found [B. L. Cohen and T. H. Handley, "Experimental Studies of (p,t) Reactions," Phys. Rev. (to be published)] that the statistical theory successfully predicts the cross sections for (p,t) reactions occurring by compound nucleus interaction in iron and palladium. Since the uncertainties in these calculations are very similar to those in the dineutron calculation (the thresholds are about the same), the dineutron calculation is probably not in error by as much as a factor of ten.

[10] The statistical theory does not predict (δ,γ) cross sections, so the results of the calculation are given in terms of $\sigma(\delta,\gamma)$ necessary to explain the experimental results.

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Magnetic Analysis of the $V^{51}(d,p)V^{52}$ Reaction*†

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The proton groups from vanadium targets bombarded with 6-Mev deuterons from an electrostatic generator have been analyzed with a 180-degree magnetic spectrograph. The ground-state Q value for the $V^{51}(d,p)V^{52}$ reaction was found to be 5.072 ± 0.008 Mev. Of the proton groups observed, twenty-three have been ascribed to vanadium and correspond to excited states in V^{52} between the ground state and an excitation energy of 3.30 Mev.

I. INTRODUCTION

INFORMATION regarding the excited states of V^{52} has been derived principally from studies of the $V^{51}(d,p)V^{52}$ reaction[1–4] and from the study of the gamma rays from the $V^{51}(n,\gamma)V^{52}$ reaction.[5] The results of these various investigations are not in good agreement. The Q value for the ground-state transition of the (d,p) reaction has been reported to be 7.80 Mev by Davidson[1] and 5.53 ± 0.15 Mev by Abramov.[2] Harvey's value[3] of 5.02 ± 0.05 Mev is in better agreement with the value of 5.079 ± 0.008 Mev which is deduced from the gamma-ray measurements.[5] The discrepancy between these various values is somewhat reduced if one assumes that a second group of protons of Q value 5.33 Mev, as measured by Davidson,[1] is the ground-state group and that the higher Q value is due to some other process. There is similar disagreement regarding the positions of the excited states of V^{52}, the gamma-ray measurements showing a considerably more complicated spectrum than would be expected from the results of the (d,p) reaction studies.

Recently, King and Parkinson[4] have reported angular distribution studies of two proton groups from the (d,p) reaction, the groups being assigned to the ground state and first excited state. Such a study was proposed by Bethe and Butler[6] as a test of the nuclear-shell model. There is some doubt regarding the interpretation of these experiments, since the gamma-ray measurements indicate that several different groups may have been involved in the measurements.

In view of these discrepancies, the measurements to be reported in this paper were undertaken in order to study the (d,p) reaction with higher-resolution apparatus than has been available to other workers.

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† These results are taken from a thesis submitted by the authors to the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Physics under the Naval Postgraduate Training Program.

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[5] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).

[6] H. A. Bethe and S. T. Butler, Phys. Rev. **85**, 1045 (1952).

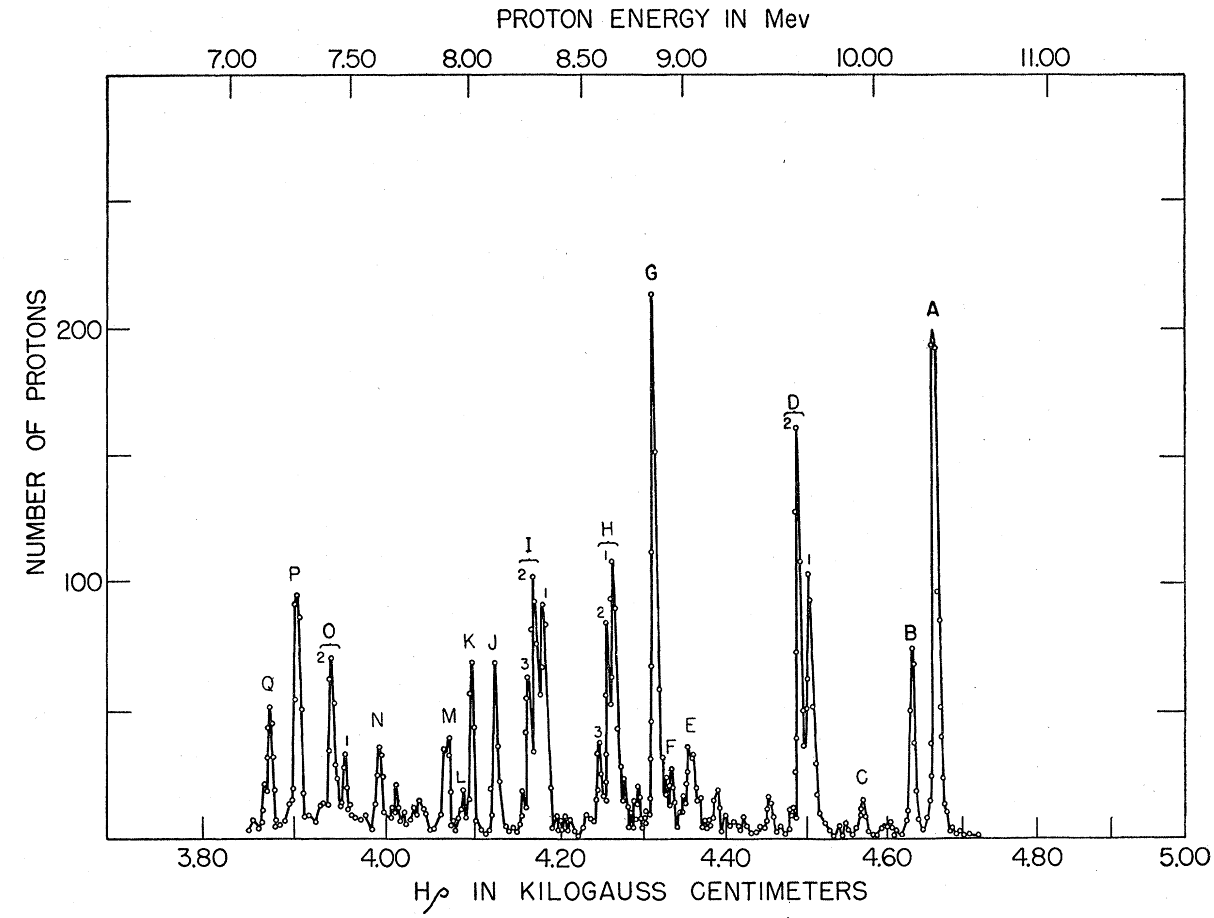

FIG. 1. Proton groups from natural vanadium target bombarded with deuterons of energy 5.74 Mev.

II. EXPERIMENTAL PROCEDURE

For these studies, the ONR electrostatic generator and a 180-degree magnetic spectrograph were used. The generator provides a deuteron beam whose energy can be varied up to 8.5 Mev, and the spectrograph makes possible the high-resolution analysis of the charged particles emitted in a direction at 90 degrees with respect to the deuteron beam. This installation has been described in a recent paper,[7] which contains references to the calibrating procedure and the methods of analyzing the data.

For this work, targets were prepared by evaporating metallic vanadium onto thin Formvar films. The evaporation process produced targets that would satisfactorily withstand several thousand microcoulombs of bombardment wihout deterioration. This process will be described in a separate publication. A chemical analysis of the metal used for the target preparation, as determined by the Vanadium Corporation of America, showed that aside from oxygen the only impurities present were 0.05 percent or less of silicon, iron, aluminum, and nitrogen. The targets, as prepared, were analyzed by studying the energy distribution of protons elastically scattered from them. These measurments showed, in addition to traces of the impurities listed above, small amounts of tantalum, potassium, and sodium, presumably from the evaporator, as well as carbon and oxygen from the Formvar backing. While natural vanadium consists of two isotopes, the abundance of V^{50} is only 0.24 percent. Since these measurements covered a region of proton energy above that in which the groups from carbon and oxygen are encountered [except for the ground-state group of $C^{13}(d,p)C^{14}$], all the intense proton groups observed presumably originate from the $V^{51}(d,p)V^{52}$ reaction. In order to insure, however, that none of the groups thus assigned originated from an impurity, each of the observed groups was studied at more than two bombarding energies. While the complexity of the observed proton spectrum and the fact that not all the proton groups were completely resolved prevented the exact determination of the masses involved, in all cases it was established that the target mass responsible for each of the peaks differed from that of V^{51} by five mass units or less. Since none of the analyses indicated the presence of contaminants within this mass range, it is

[7] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. 91, 1468 (1953).

TABLE I. Reaction energies from $V^{51}(d,p)V^{52}$.

Group	Relative intensity for E_d=5.74 Mev	Q value in Mev	Level energy in Mev
A	0.93	5.072±0.008	0
B	0.36	4.941±0.008	0.131±0.011
C	0.07	4.654±0.008	0.418±0.011
D_1	0.50	4.292±0.008	0.780±0.011
D_2	0.75	4.238±0.008	0.834±0.011
E	0.21	3.670±0.008	1.402±0.011
F	0.13	3.597±0.008	1.475±0.011
G	1.00	3.527±0.008	1.545±0.011
H_1	0.50	3.319±0.008	1.753±0.011
H_2	0.38	3.287±0.008	1.785±0.011
H_3	0.20	3.231±0.015	1.841±0.017
I_1	0.43	2.984±0.008	2.088±0.011
I_2	0.48	2.941±0.012	2.131±0.015
I_3	0.33	2.922±0.012	2.150±0.015
J	0.40	2.765±0.008	2.307±0.011
K	0.39	2.657±0.008	2.415±0.011
L	0.10	2.614±0.008	2.458±0.011
M	0.22	2.547±0.008	2.525±0.011
N	0.21	2.224±0.008	2.848±0.011
O_1	0.20	2.070±0.008	3.002±0.011
O_2	0.41	2.021±0.008	3.051±0.011
P	0.52	1.883±0.008	3.189±0.011
Q	0.29	1.766±0.008	3.306±0.011

considered probable that all the groups identified as originating in V^{51} have been correctly assigned.

III. RESULTS

The proton groups having energies between 10.5 and 7.0 Mev observed from a vanadium target bombarded with 5.74-Mev deuterons are shown in Fig. 1. The labeled groups in the figure are assigned to the $V^{51}(d,p)V^{52}$ reaction. As has been mentioned, these assignments were made partly on the basis of the observed shift in energy of the groups with changes in the deuteron energy. Thus, the groups in Fig. 1 having an energy greater than 9.5 Mev were also studied at a bombarding energy of 5.00 Mev. The lower-energy groups in the figure were also measured for a bombarding energy of 6.48 Mev. As can be seen from the figure, a number of low-intensity groups are present, and, except for the one at $H\rho=4.60$, no assignment has been made. The group at $H\rho=4.60$ originates in the ground-state $C^{13}(d,p)C^{14}$ reaction. It is clear that, as would be expected from the shell model, the level scheme of V^{52} is of considerable complexity.

The Q values calculated for these various groups, together with their relative intensities, are tabulated in Table I. Also listed are the positions of the excited states, as deduced from the present work. The ground-state Q value is in excellent agreement with the value of 5.079±0.008 Mev, which is obtained by subtracting the deuteron binding energy from the ground-state gamma-ray energy measured by Bartholomew and Kinsey[5] for the (n,γ) reaction.

An energy-level diagram for V^{52}, based on the present results, is shown in Fig. 2. It is probable that several of the levels shown, E and M, for example, are actually more complex, but no attempt was made to resolve further the groups shown in Fig. 1. In contrast to previous work on the (d,p) reaction, there is agreement, within the experimental errors, between these results and those from the (n,γ) reaction. With the exception of the weakest gamma ray, in the region where the two sets of measurements overlap, all of the radiations observed by Bartholomew and Kinsey can be assigned to transitions between the capturing state in V^{52} at 7.305 Mev and the various levels shown in Fig. 2. In the figure, the vertical lines represent these gamma-ray transitions. The letters associated with each gamma ray are those used by Bartholomew and Kinsey. In agreement with their results, no indication was found for an isomeric state at 0.25 Mev reported by Renard.[8]

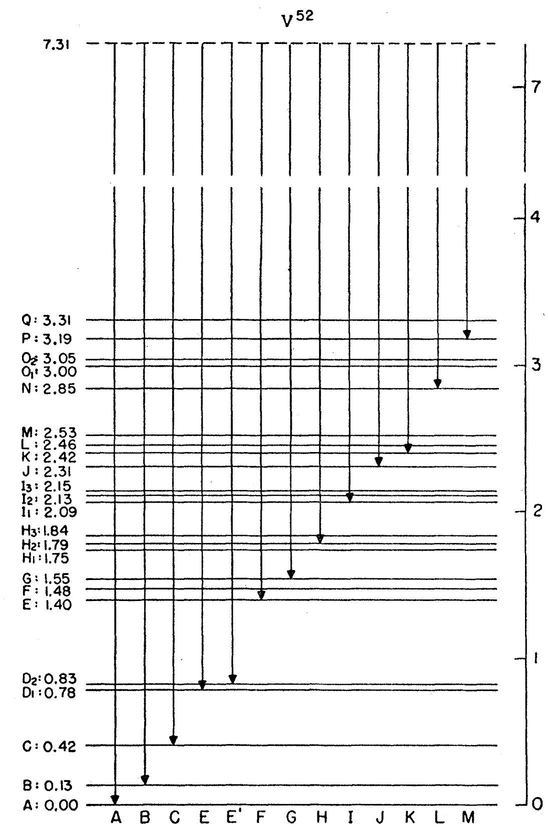

FIG. 2. Energy levels of V^{52}. Vertical lines represent possible assignments of the gamma rays from the (n,γ) reaction.

Although there is good over-all agreement between the results of the (d,p) and (n,γ) studies, it is puzzling that except for level P, the levels as determined by the gamma-ray work are all between 10 and 20 kilovolts higher than the corresponding levels as determined from the proton groups. No reason has been discovered for this discrepancy, which is within the combined errors of the two sets of measurements.

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[8] G. A. Renard, Ann. Phys. 5, 385 (1950).