States of Low Excitation in O^{18}†

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A new state in O^{18} at an excitation energy of 3.555±0.013 Mev is established by a proton group from the reaction $O^{17}(d,p)$ with $Q=2.262\pm0.015$ Mev and by a deuteron group from the reaction $O^{18}(d,d')$ with $Q=-3.551\pm0.019$ Mev. A level reported by Ahnlund at 1.986±0.014 Mev is confirmed. No evidence is found for states between these two, in particular for one reported by Holmgren and coworkers at 2.445 Mev.

I. INTRODUCTION

In working out the consequences of a central field assumption for nuclei, those nuclides with two or three particles or holes, besides closed shells, occupy an especially important place. Recently Elliott and Flowers[1] and Redlich[2] have calculated energy levels, wave functions, and a number of associated nuclear properties, for two and three particles moving in the field of doubly magic O^{16}. Because of the scarcity of data for states in O^{18} and F^{18}, extensive comparison with experiment was possible only for F^{19}. The present investigation is part of an effort to obtain more experimental information concerning the two-particle system.

II. EXPERIMENTAL PROCEDURE

The 42-in. Michigan cyclotron makes available in a shielded room next to the machine a few tenths microampere of deuterons, monoenergetic to within 15 kev, at a mean energy near 7.8 Mev. Charged reaction products are analyzed by a one-meter radius, 90° deflection, double-focusing magnet with an ultimate resolution of about 5 kev at 10 Mev, and a solid angle of 6×10^{-4} steradian. The instrumentation is described in another paper.[3]

The present work was made possible by the loan of 20 mg of oxygen gas, enriched to about 45% in O^{18} and about 1½% in O^{17}, from Professor A. O. Nier of the University of Minnesota. The oxygen was exploded with hydrogen to make enriched water vapor, and the vapor allowed to react with evaporated films of lithium metal to form targets of LiOH. During the chemical reaction it was necessary to have the lithium in intimate contact with a solid support to prevent wrinkling; therefore the evaporation was made onto a 0.02 mg/cm² film of Formvar backed by a glass plate. After formation of the hydroxide, strips were peeled from the plate and mounted between Formvar films in a target frame. Lithium hydroxide converts slowly to the carbonate in air, so that it was necessary to store the target in vacuum between runs. For high intensity, a moderately thick target was used. The 1.2 mg/cm² surface density chosen led in transmission measurements to proton peaks at 10 Mev of width about 50 kev, and to deuteron peaks at 4 Mev of width about 70 kev. (Groups from Li were wider because of the rapid change in reaction product energy with angle.)

Particles were detected at the image plane of the analyzer magnet by 1 in.×12 in. Kodak NTB nuclear emulsions, each plate covering a range in energy of 15%. Proton and deuteron spectra were obtained at laboratory angles of 28.5°, 49.7°, 58.5°, 68.5°, and 89.7°. The measurement of momentum and range established the particle type. An hour's run yielded several hundred tracks, typically, in the weak groups resulting from reactions leading to excited states in O^{18}.

III. EXPERIMENTAL RESULTS

Proton and deuteron groups were identified corresponding to known states in Li^6 and Li^7, in C^{12} and C^{13}, and in O^{16}, O^{17}, O^{18}, and O^{19}.

In the deuteron spectrum at 49.7°, Fig. 1(a), a new group appears which, if due to inelastic scattering of deuterons from O^{18}, corresponds to an excitation of that nucleus by 3.551±0.019 Mev. A portion of the spectrum at 68.5°, Fig. 1(b), shows the new group focussed now at higher energy than the nearby Li^6 group; analysis of the shift in energy with angle of the unknown group restricts the mass number of its target nucleus to 18±1. $A=17$ is not possible because the very well investigated O^{17} level diagram shows no state at the required excitation energy. Although the situation in F^{19} is less clear-cut,[4] again no state has been found at this excitation. The fact that in the present work no proton groups are found from the high-yield stripping reaction $F^{19}(d,p)$ is a stronger argument that the new deuteron group is not from $F^{19}(d,d')$.

The proton spectrum at 49.7°, Fig. 2(a), shows a new group which, if due to the reaction $O^{17}(d,p)$ has a $Q=2.262\pm0.018$ Mev. The group can be seen only for a narrow range in angle, due to the encroachment of groups from $C^{12}(d,p)$ and $O^{16}(d,p)$, but appears at 58.5°, Fig. 2(b), with an energy which requires for the target nucleus a mass number $A=17\pm2$. Target nuclei O^{16} and O^{18} are excluded because the observed Q is greater than the maximum possible for these nuclei. N^{14} and Ne^{20} are excluded because the Q's calculated

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[1] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955).
[2] M. G. Redlich, Phys. Rev. **99**, 1427 (1955), and **95**, 448 (1954).
[3] Bach, Childs, Hockney, Hough, and Parkinson, Rev. Sci. Instr. (to be published).
[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955), and references therein.

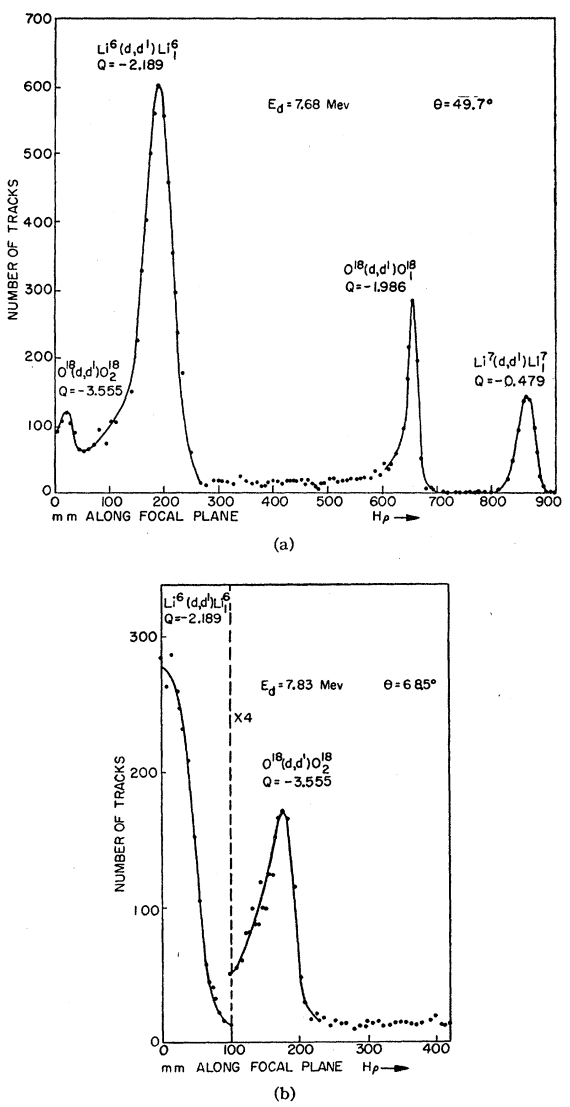

FIG. 1. Deuterons scattered inelastically from a target of LiOH enriched in O^{17} and O^{18}, (a) at 49.7° (E_d=7.68 Mev) and (b) at 68.5° (E_d=7.83 Mev). The state of excitation of a residual nucleus is indicated by a subscript.

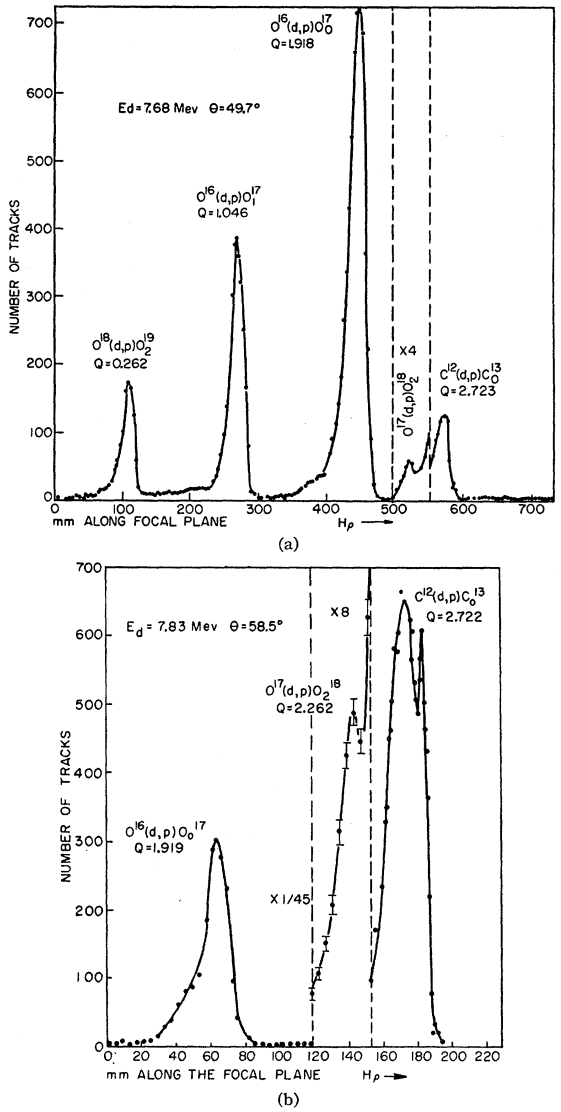

FIG. 2. Protons from (d,p) reactions in a target of LiOH enriched in O^{17} and O^{18}, (a) at 49.7° (E_d=7.68 Mev) and (b) at 58.5° (E_d=7.83 Mev). The state of excitation of a residual nucleus is indicated by a subscript.

from the observations differ, by 80 kev and over 400 kev respectively, from those of the nearest known groups in these well studied reactions. The group might result from the reaction $F^{19}(d,p)F^{20}$, Q_8=2.178 Mev,[4] since the Q calculated from the observations differs from this by only 30 kev, or two standard deviations. However, the absence of all of the many other groups from this reaction makes this explanation unlikely.

Finally, the coincidence of excitation energies in O^{18}, which occurs when the new groups are assumed to result from $O^{18}(d,d')$ and $O^{17}(d,p)$ reactions, respectively, may be considered a confirmation of the assignments. A best value for the excitation energy of the new state is 3.555±0.013 Mev.

The (d,d') excitation energy quoted is calculated[3] from the observed displacement of the unknown group from the $Li^6(d,d')$ peak shown in Fig. 1(a). An uncertainty of ±0.5° in the incident beam direction is the principal source of the error given. The (d,p) Q-value quoted is calculated[3] from the separation of the unknown proton group in Fig. 2(a) from the ground-state group of the reaction $O^{16}(d,p)$. Here the principal uncertainty is in the measurement of the peak position of the very weak unknown group. The excitation energy which follows from the Q-measurement assumes for the $O^{17}(d,p)O^{18}$ reaction leading to the ground state a Q-value[5] Q_0=5.821±0.010 Mev.

Ahnlund[5] has found a state in O^{18} at an excitation energy of 1.986±0.013 Mev. In the present work, proton groups from the reaction $O^{17}(d,p)$ corresponding to this state are observed at 28.5° and 89.7°; a deuteron

[5] K. Ahnlund, Phys. Rev. 96, 999 (1954). See also reference 4.

group from the reaction $O^{18}(d,d')$ leading to this state is seen at 58.5°. Since Ahnlund's Q has been used in a determination[3] of the incident beam energy, an independent Q-value cannot be given, but the existence of the state is well verified.

Between the states of excitation 1.986 and 3.555 Mev, no evidence is found for any level in O^{18}. In Fig. 3 are assembled the data having a bearing on this question. Numbers of particles per unit momentum are plotted as ordinate against a single abscissa representing excitation energy in O^{18}—with the assumption that the reactions $O^{17}(d,p)$ and $O^{18}(d,d')$ are responsible for the protons and deuterons observed. At the ends of the excitation energy scale are shown proton or deuteron groups leading to the 1.986- or 3.555-Mev states; the intensity of each group is reduced by the numerical factor written at the peak. Upper bounds on the cross sections for transitions to states of excitation E, $1.998<E<3.555$, may be estimated by comparing the statistical errors at E with the reduced peak heights. These bounds are given in Table I. In Fig. 3, attention is called to the excitation energy $E=2.445$ Mev, where a state is reported by Holmgren and co-workers.[6]

The $O^{17}(d,p)O^{18}$ spectrum of Ahnlund[5] offers an extraordinarily clear view of the region of excitation

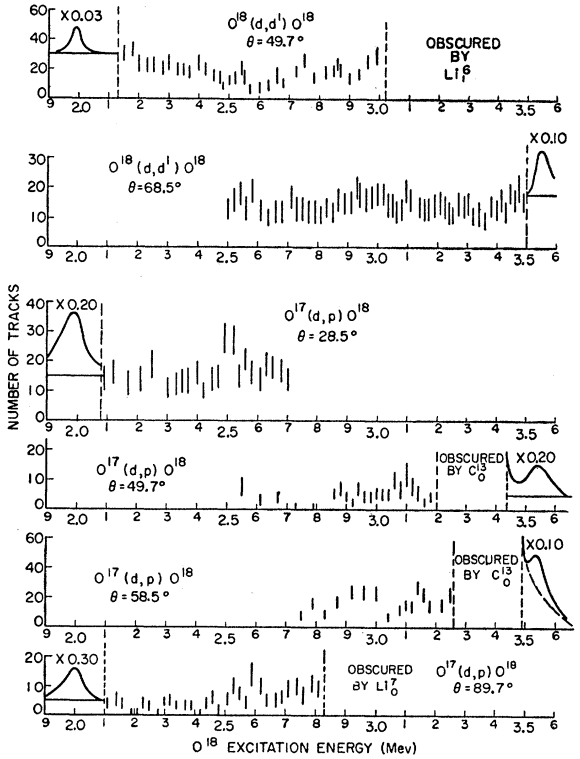

FIG. 3. Proton and deuteron spectra for the region of excitation in O^{18} between the states at 1.986 Mev and 3.555 Mev. In each spectrum is shown a particle group corresponding to one or the other established state, reduced in intensity by the numerical factor written at the peak. For upper limits on the cross sections leading to possible states of excitation E, $1.986<E<3.555$, see the text and Table I.

[6] Holmgren, Hanscome, and Willett, Phys. Rev. **98**, 241 (A) (1955).

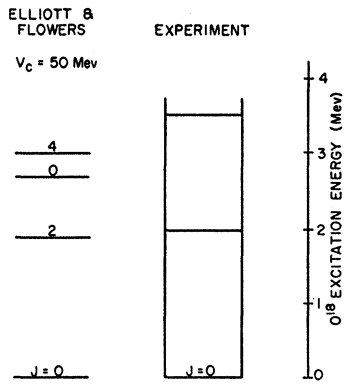

FIG. 4. Comparison of experiment with the theoretical level diagram of Elliott and Flowers.

from 0 to 1.986 Mev, and we cannot provide more restrictive limitations on the intensity of transitions to possible states in this region.

IV. DISCUSSION

The energy level diagram for O^{18} indicated by the experiments is shown in Fig. 4. Adjacent is the level diagram predicted by Elliott and Flowers[1] with the constant V_C in their interaction potential chosen equal to 50 Mev. With this choice, the absolute binding energy of a neutron in O^{17} is predicted somewhat larger than observed, but by an amount which cannot be deduced from their published results. A smaller V_C leads to a still smaller spacing between first and second excited states than shown. Thus the agreement between theory and experiment is not good, and alteration of the form of the interaction energy assumed for the two neutrons outside O^{16} is indicated.

On the other hand, for less speculative comparison with the theory, experimental spins and parities are very much needed. In this laboratory the $O^{17}(d,p)O^{18}$ angular distributions are being measured, and should yield the parities of the three known states. For the determination of spins, $O^{18}(\alpha,\alpha')$ angular distribution measurements have been proposed[7] and are under consideration.

V. ACKNOWLEDGMENTS

The loan from Professor Nier of oxygen enriched in O^{17} and O^{18} is gratefully acknowledged. Throughout the experiment, R. W. Hockney provided valuable assist-

TABLE I. Upper bounds on the differential cross section $\sigma(\theta,E)$ for $O^{17}(d,p)$ or $O^{18}(d,d')$ reactions at laboratory angle θ leading to possible states of excitation energy E in O^{18}. The bounds are on the ratio of $\sigma(\theta,E)$ to the cross section $\sigma(\theta,E_0)$ leading to a known state in O^{18} at excitation energy $E_0=1.986$ or 3.555 Mev. All energies are given in Mev.

Reaction	θ	Upper bound for $\sigma(\theta,E)/\sigma(\theta,E_0)$	E_0	Range of E
$O^{18}(d,d')$	49.7°	0.03	1.986	1.99–3.00
	68.5°	0.08	3.555	2.50–3.55
$O^{17}(d,p)$	28.5°	0.20	1.986	1.99–2.70
	49.7°	0.20	3.555	2.55–3.16
	58.5°	0.20	3.555	2.72–3.23
	89.7°	0.30	1.986	2.50–3.55

[7] A. M. Lane (private communication).

ance. It is a pleasure to thank O. M. Bilaniuk for help in taking data, and Quin McLaughlin for the careful reading of many of the plates.

The magnetic analysis of the incident beam and of the reaction products has been the joint undertaking of many people. To them, and in particular to W. C. Parkinson who initiated the development, we express our appreciation.

Finally, we thank R. D. Pittman, R. H. White, and H. M. Nye, of the cyclotron technical staff, for their many contributions to the development and maintenance of the apparatus.

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Disintegration of Ge^{68}†

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The isotope Ge^{68} has been prepared by the bombardment of zinc with 37-Mev alpha particles and separated chemically. The half-life of Ge^{68} is 275±20 days, as determined by comparison with a Co^{60} standard over 10 months. The positron spectrum was measured with a thick-lens magnetic spectrometer. Positron groups from Ga^{68} have maximum energies of 1.94 and 0.92 Mev and relative intensities of 1 and 0.04, respectively; no positrons from Ge^{68} were observed above 0.3 Mev. The scintillation spectrum shows annihilation radiation and a 1.02-Mev gamma ray from Ga^{68}. Comparison of areas under these two peaks, corrected for crystal efficiency, indicates that there are 14.4±1.7 positrons per 1-Mev quantum. Within the probable error, this result is compatible with the decay of Ge^{68} by electron capture alone.

I. INTRODUCTION

THE radioactive isotope Ge^{68} probably was first produced in 1938 by Mann[1] who described, but did not definitively assign, a long-lived (~195 day) germanium activity obtained in the bombardment of zinc with 17-Mev alpha particles. Hopkins[2,3] obtained Ge^{68} among 38 nuclear species formed through spallation reactions in the bombardment of arsenic with 190-Mev deuterons. He reported a half-life of 250 days and decay by electron capture. Batzel *et al.*[4] found a long-lived activity in the germanium fraction from the high-energy spallation products of copper, which was comparable with that expected for Ge^{68}.

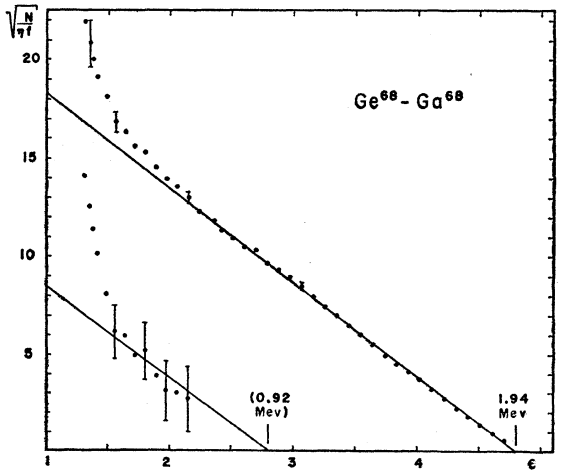

FIG. 1. Fermi plot of the positron spectrum from $Ge^{68}-Ga^{68}$.

Since so little information was available on Ge^{68}, it was considered worth while to produce a sample of this isotope directly, to redetermine its half-life, and to verify the absence of gamma rays and positrons.

II. SOURCE PREPARATION

The Ge^{68} sample was prepared by bombarding a zinc-coated copper probe with 220 microampere-hours of 37-Mev alpha particles in the Crocker Laboratory cyclotron of the University of California, leading to the reaction $Zn^{66}(\alpha,2n)Ge^{68}$. The zinc layer on the probe was dissolved in cold concentrated HCl containing Ge carrier. $GeCl_4$ was distilled into dilute H_2SO_4 and GeS_2 precipitated by bubbling H_2S through the solution. The germanium sulfide was washed and dissolved in NH_4OH, then transferred to thin Tygon foils mounted on Lucite source holders.

III. HALF-LIFE DETERMINATION

Beginning 330 days after bombardment, the activity from a sample of Ge^{68} was determined weekly with a well-shielded Victoreen 1B67 Geiger tube in fixed geometry. A standard source of Co^{60} was counted immediately after every Ge^{68} count. The ratio of the two activities was plotted, thus eliminating the effect of any slow drift in the efficiency of the counting device. The measurements extended over 300 days. Using Brosi and Ketelle's[5] value of 5.38±0.03 years for the half-life of Co^{60}, a half-life of 275±20 days was obtained for Ge^{68}.

† This work was supported by a grant from the National Science Foundation and by a research grant from the Graduate School of the University of Oregon.
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[2] H. H. Hopkins, Jr. and B. B. Cunningham, Phys. Rev. **73**, 1406 (1948).
[3] H. H. Hopkins, Jr., Phys. Rev. **77**, 717 (1950).
[4] Batzel, Miller, and Seaborg, Phys. Rev. **84**, 671 (1951).
[5] Way, King, McGinnis, and van Lieshout, *Nuclear Level Schemes* (U. S. Atomic Energy Commission, Washington, D. C., 1955), p. 70.