ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

Progress Report

UNIVERSITY OF MICHIGAN CYCLOTRON

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Project 2170

U.S. ATOMIC ENERGY COMMISSION
CONTRACT NO. AT(11-1)-275

July 1955

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I. INTRODUCTION

During the year covered by this report the greatest part of the effort of the Michigan Cyclotron Group was devoted to work on experimental and theoretical problems in nuclear spectroscopy. The effort expended on machine instrumentation, with one exception, was concerned with maintenance and minor improvements. The results of much of the work will soon appear in print and only a brief description will be given here.

II. MACHINE OPERATION AND IMPROVEMENT

The cyclotron was in use approximately 22 hours per day, with the exception of Saturday and Sunday nights. The total down time due to machine failures amounted to approximately two weeks. An additional three weeks were spent in machine improvement. The one major improvement incorporated this year was the installation of a new 75-kva oscillator power supply. The primary motivation of the installation was to eliminate the serious fire hazard but, in addition, more reliable operation was obtained. The system, connected in 6-phase single wye, with powerstat control of the output voltage, includes a constant-current network and an L-C filter. The addition of the filter aids materially in the reduction of "ripple" in the deuteron beam. Ripple is particularly objectionable, due to the fact that the external beam is a steep function of the r.f. dee voltage.

During the past year some difficulty was encountered because of aperiodic shifts in the median plane of the cyclotron beam. The shift was due to insulation leakage in the two lower coils of the cyclotron magnet, the leakage being a result of condensation of moisture and an accumulation of oil and carbon dust over a period of five years. The coils were reinsulated and covered when the oscillator power supply was installed.

An improvement which can hardly be classed as minor was the installation of an 8.2-ton air-conditioning unit. Because of the long running schedule, with attendant heat dissipation, the mean temperature in the cyclotron area was approximately 95°F, with a relative humidity of 90-95%. Since the addition of the air-conditioning unit, more reliable results have been obtained both from the machine and from the personnel.

A fine control on the cyclotron oscillator frequency was installed for convenience in tuning and for control of the beam energy. It is planned to establish the focusing magnet field at a definite value with the aid of a nuclear moment fluxmeter in the gap. When this is done, the beam current within the energy band selected by the focusing magnet will be maximized by slightly adjusting the oscillator frequency.

Additional improvements included the installation of a better monitor counter and beam current integrator, new vacuum control and vacuum safety system, higher capacity power lines to the cyclotron unit, and line voltage regulators for electronic equipment. The medium-resolution system was improved mechanically and electrical interconnections were permanently installed. The nuclear-moment field-stabilizer system for the analyzer magnet was completed.

III. INSTRUMENTATION FOR RESEARCH

A. TARGET PREPARATION

In preparing thin targets for use with the medium-resolution system, each element investigated requires the adoption of new techniques and tricks. To facilitate target preparation, a versatile evaporator unit was constructed and, while it is neither elaborate nor unique, it does add materially to the laboratory facilities. Provisions are included for rapid evacuation and for performing four evaporations with a single evacuation.

B. PHOTOGRAPHIC-PLATE SCANNER

An Image Orthicon television camera has been used to convert the light pattern from a microscope focused on a nuclear emulsion scene to an electrical pattern. Circuitry for a high-speed automatic analysis of the electrical pattern is being built. A prototype circuit has given low speed but reliable detection of 10-mev proton tracks.

C. MULTICHANNEL PULSE-HEIGHT ANALYZER

Construction is in progress on a 100-channel Hutchinson-Scarrott-type pulse-height selector. In addition to its many obvious uses it is planned for automatic recording of the neutron-time-of-flight data.

IV. THE EXPERIMENTAL PROGRAM

A. EXCITED STATES OF O^{17}

The nucleus O^{17} is of interest since it represents a doubly-closed shell core plus one neutron. In addition to the question of how the core is disturbed to produce the nonsingle-particle excited states, of particular interest is the energy difference between the d5/2 and d3/2 single-particle levels, since this represents the energy of the spin-orbit coupling in the first d-shell.

The proton spectrum obtained at 20° with the medium-resolution system from a thin "mylar" target is shown in Fig. 1. In addition to proton groups from carbon and oxygen, an intense group from the reaction $H_1(d,p)H_2$ is observed. (The resolution used does not represent the ultimate of the system, but only that required for this particular investigation. See Section IV-C.)

Angular distributions of the protons from the reaction $O^{16}(d,p)O^{17}$ have been obtained for the seven lowest-lying levels of O^{17}. The distributions for the ground, first, second, and third excited states are shown in Fig. 2. They are included to indicate the "standard" types of angular distributions obtained in stripping reactions. The distribution for the ground and first excited states are typical of single-particle levels while the distributions for the second and third excited states are typical of levels which arise from configuration mixing. Our interest in the stripping reaction goes beyond the assignment of parities to levels because of the conviction that an understanding of the angular distributions will yield information about the interactions of the nucleons in the nucleus.

The results of this research indicate the following. The ground, first, and fifth excited states are the single-particle levels 1d5/2, 2s1/2, and 1d3/2, respectively. The spin-orbit coupling energy of the first d-shell is 5.10 mev, in agreement with the results of Adair obtained from inelastic neutron scattering. The other four levels are odd parity states believed to be formed by removing a p1/2 proton from the O^{16} core and coupling the p1/2 hole to the $(2s,1d)^2$ configuration of F^{18}. This leads to levels of (1/2-), (7/2-), (3/2-), and (5/2-) for the second, third, fourth, and sixth states, respectively, in agreement with the levels of the mirror nucleus F^{17}.

One difficulty arises in this interpretation. The angular distribution for the second excited state indicates that the neutron is captures with two units of orbital angular momentum. This does not permit a negative parity state or a spin of 1/2 but rather implies that the level must be either (3/2+)

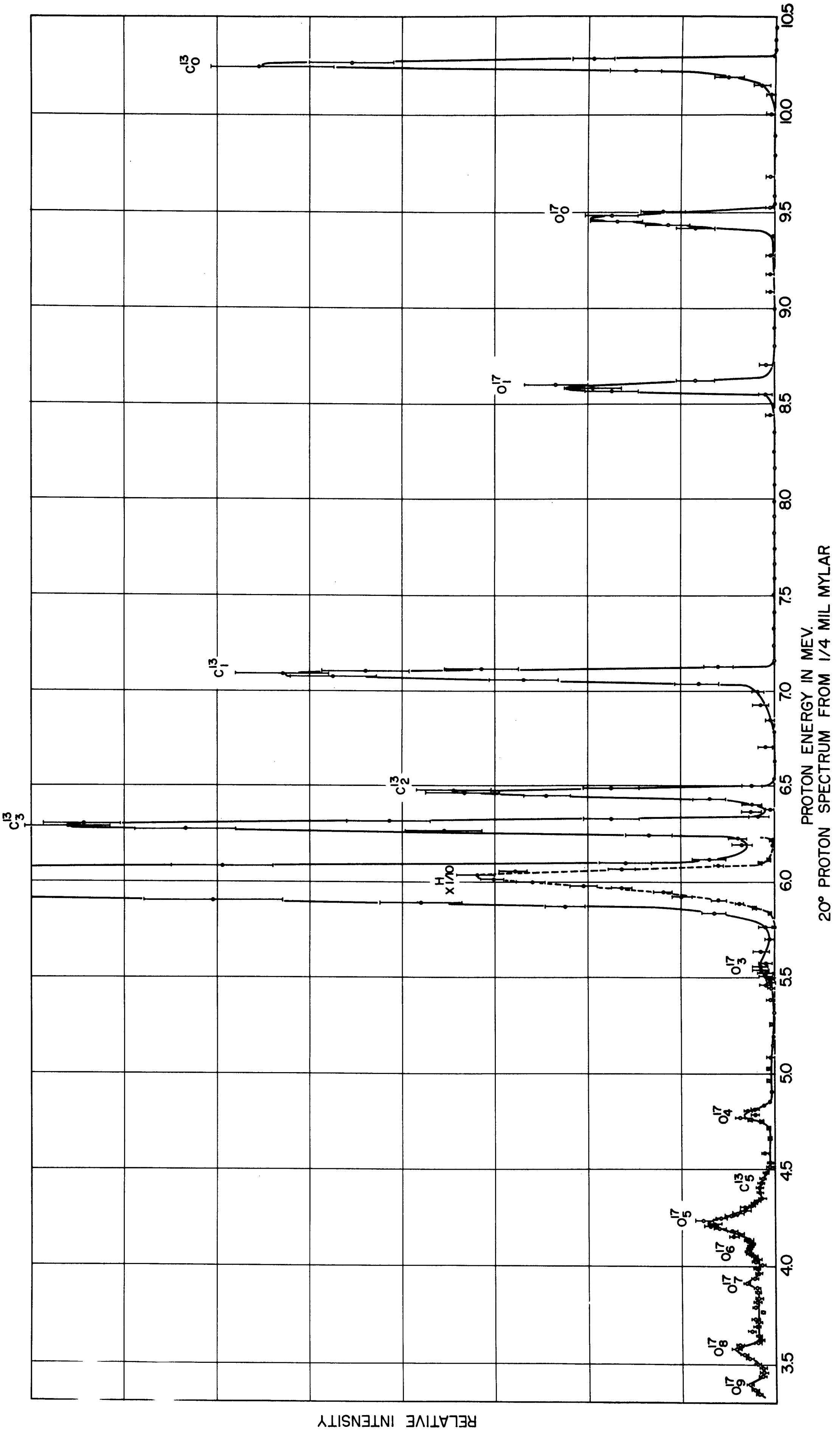

RELATIVE INTENSITY
PROTON ENERGY IN MEV.
20° PROTON SPECTRUM FROM 1/4 MIL MYLAR
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
C^{13}_0
O^{17}_0
O^{17}_1
C^{13}_1
C^{13}_2
C^{13}_3
H
x 1/10
O^{17}_3
O^{17}_4
C^{13}_5
O^{17}_5
O^{17}_6
O^{17}_7
O^{17}_8
O^{17}_9

Fig. 1

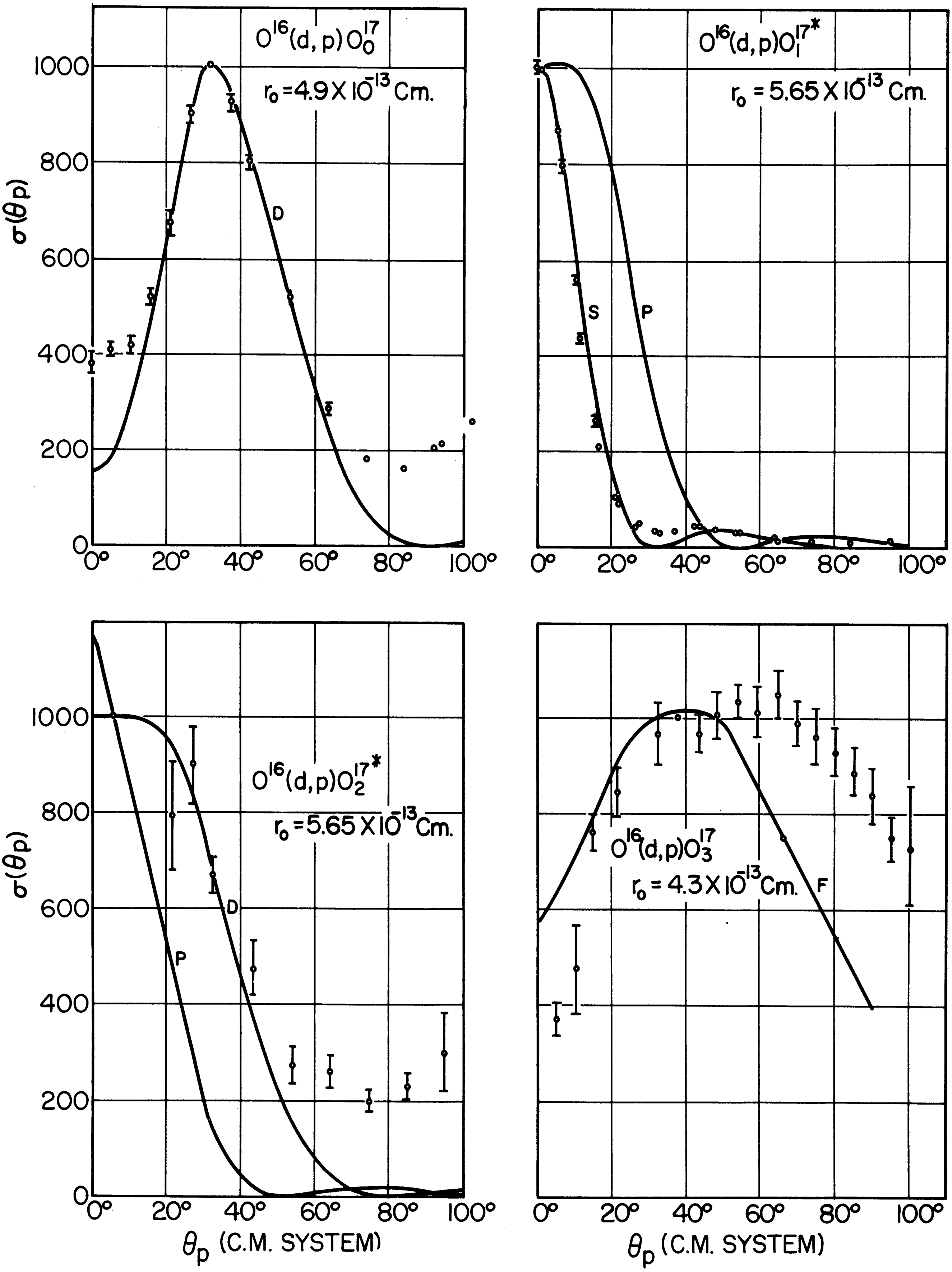

$O^{16}(d,p)O_0^{17}$
$r_0 = 4.9 \times 10^{-13}$ Cm.
D
$O^{16}(d,p)O_1^{17*}$
$r_0 = 5.65 \times 10^{-13}$ Cm.
S
P
$O^{16}(d,p)O_2^{17*}$
$r_0 = 5.65 \times 10^{-13}$ Cm.
D
P
$O^{16}(d,p)O_3^{17}$
$r_0 = 4.3 \times 10^{-13}$ Cm.
F
$\sigma(\theta_p)$
0
200
400
600
800
1000
0°
20°
40°
60°
80°
100°
θ_p (C.M. SYSTEM)

Fig. 2

or (5/2+). Theoretical calculations based on the shell model and results obtained from the study of other reactions predict a spin of (1/2-). Thus, the results of stripping are in direct conflict. At least one other similar conflict is known, namely the first excited state of B^{11}.

B. EXCITED STATES OF C^{13}

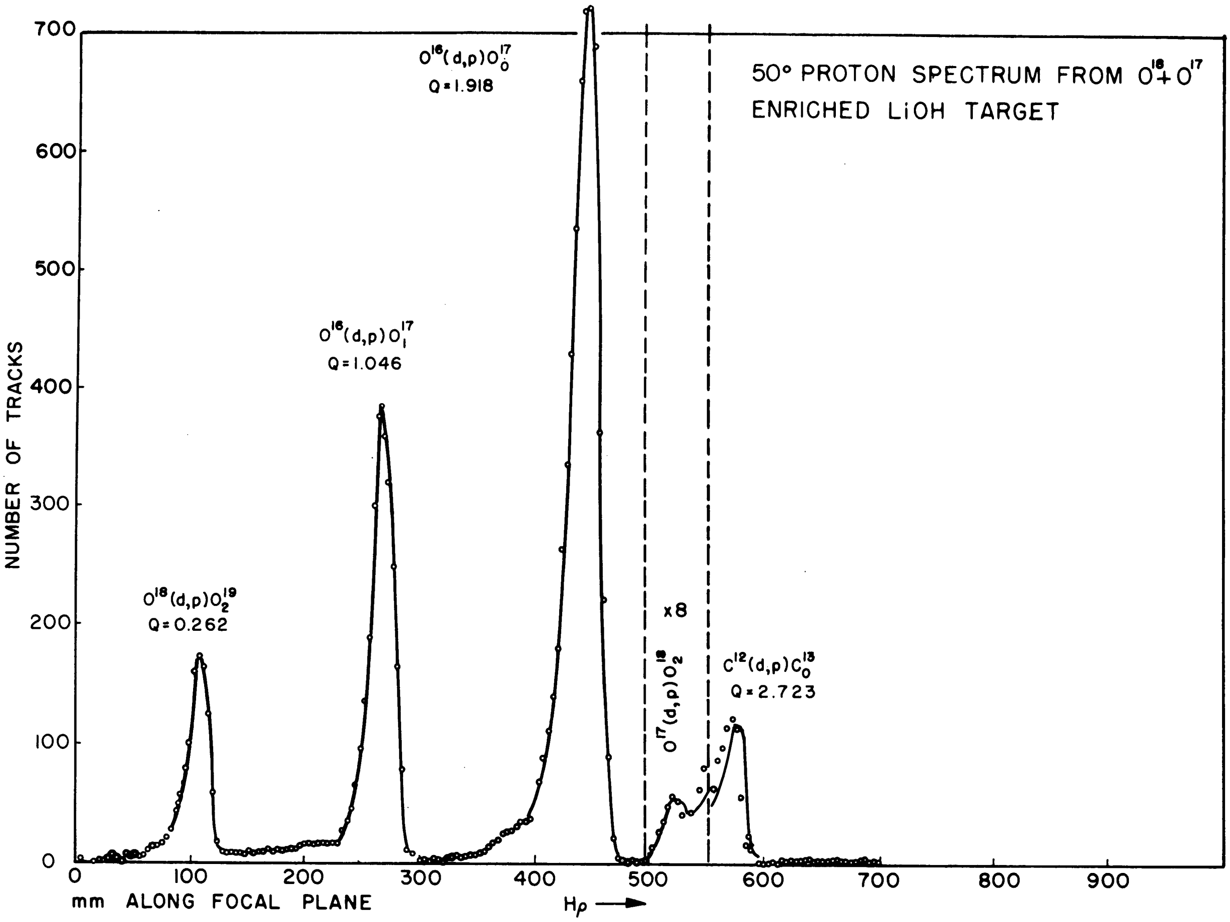
In the reaction $C^{12}(d,p)C^{13}$, no new levels of C^{13} were found below an excitation of 4 mev. Any observed levels in this region must be less intense by a factor 100 than those observed. While angular distributions were not accurately measured, rough data indicate agreement with the parities previously assigned.

C. EXCITED STATES OF O^{18}

O^{18} and F^{18} are almost ideal nuclei for application of the full machinery of theoretical nuclear spectroscopy. The experiments, however, are difficult, mainly because of the low natural abundance of O^{17} and O^{18}. Professor A. O. Nier has made possible the present study by furnishing a sample of gas highly enriched in O^{17} and O^{18}. The gas was exploded with hydrogen to yield enriched H_2O, and the water subsequently reacted with an evaporated film of lithium metal to form LiOH. Small fragments of LiOH supported between thin layers of Formvar formed a satisfactory target. It was necessary to discharge the films during the deuteron bombardment to prevent their breaking due to electrostatic forces. This was done by means of an electron beam from a nearby filament.

At the time the experiment was begun, no excited states in O^{18} were known. In the course of the work, a level at 1.98 mev was reported by K. Ahnlund of the Nobel Institute of Stockholm, and a level at 2.45 mev by H. D. Holmgren, et al., of the Naval Research Laboratory. The results of the present experiment confirm the 1.98-mev level, but no evidence for the state of 2.45 mev was found. Any proton group from $O^{17}(d,p)O^{18}$ leading to this state has, at 50°, an intensity less than 10% of the group leading to the 1.98-mev state. For the reaction $O^{18}(d,d')O^{18}$, the upper limit at 70° is 5%. In a private communication Holmgren reported the 2.45-mev group to be about half as intense as the 1.98-mev group, but stated that further work is needed before his assignment can be considered certain.

The spectra (Figs. 3 and 4) show a new state in O^{18} at an excitation energy of 3.54 mev. Proton groups from $O^{17}(d,p)$ and deuteron groups from O^{18} (d,d') are observed, in each case at two different angles. From the change with angle of the reaction product kinetic energies, the state is assigned to a nuclide of mass 18 ± 1. The Q for the deuteron group does not correspond to any known state of O^{17} or F^{19}. Further, the Q for the proton group is greater


50° PROTON SPECTRUM FROM O16+O17
ENRICHED LiOH TARGET
O16(d,p)O17 0
Q=1.918
O16(d,p)O17 1
Q=1.046
O18(d,p)O19 2
Q=0.262
x8
O17(d,p)O18 2
C12(d,p)C13 0
Q=2.723
NUMBER OF TRACKS
mm ALONG FOCAL PLANE
Hρ

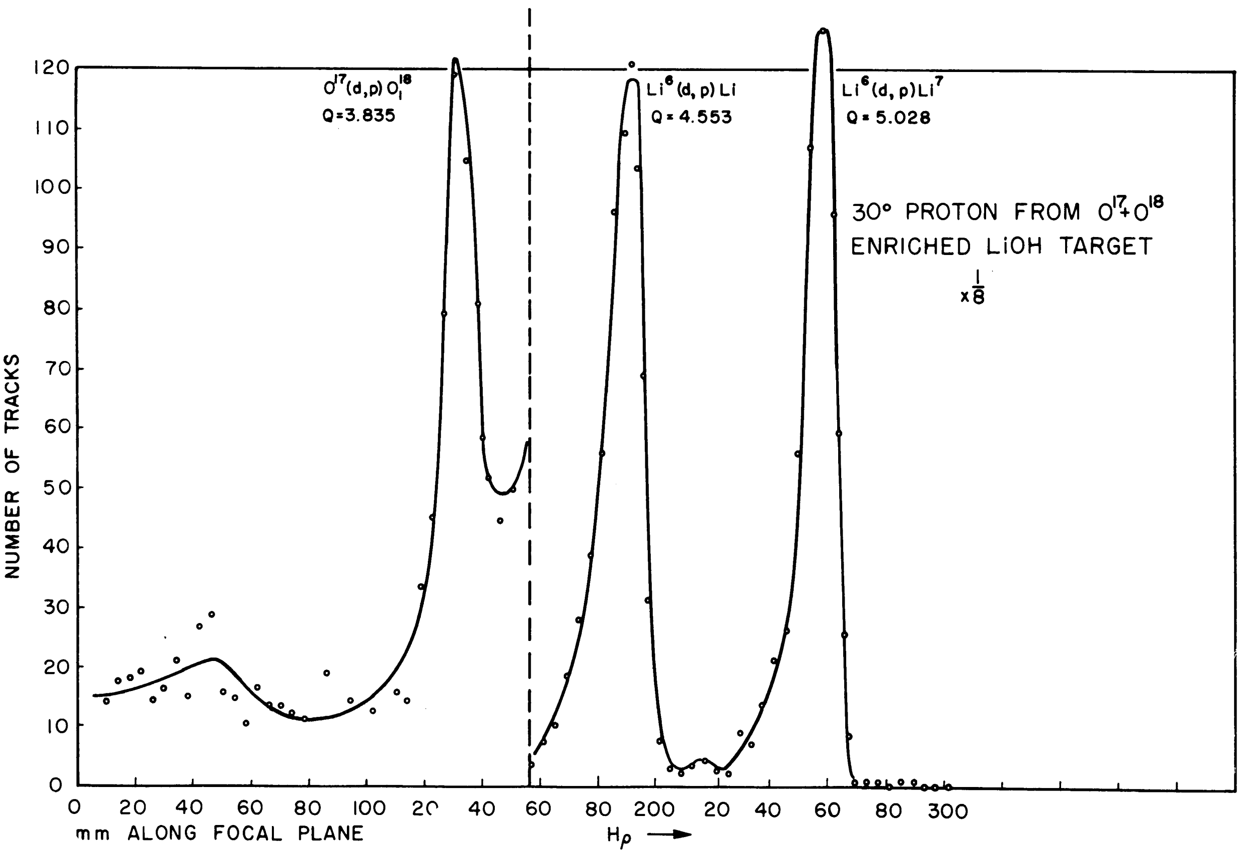
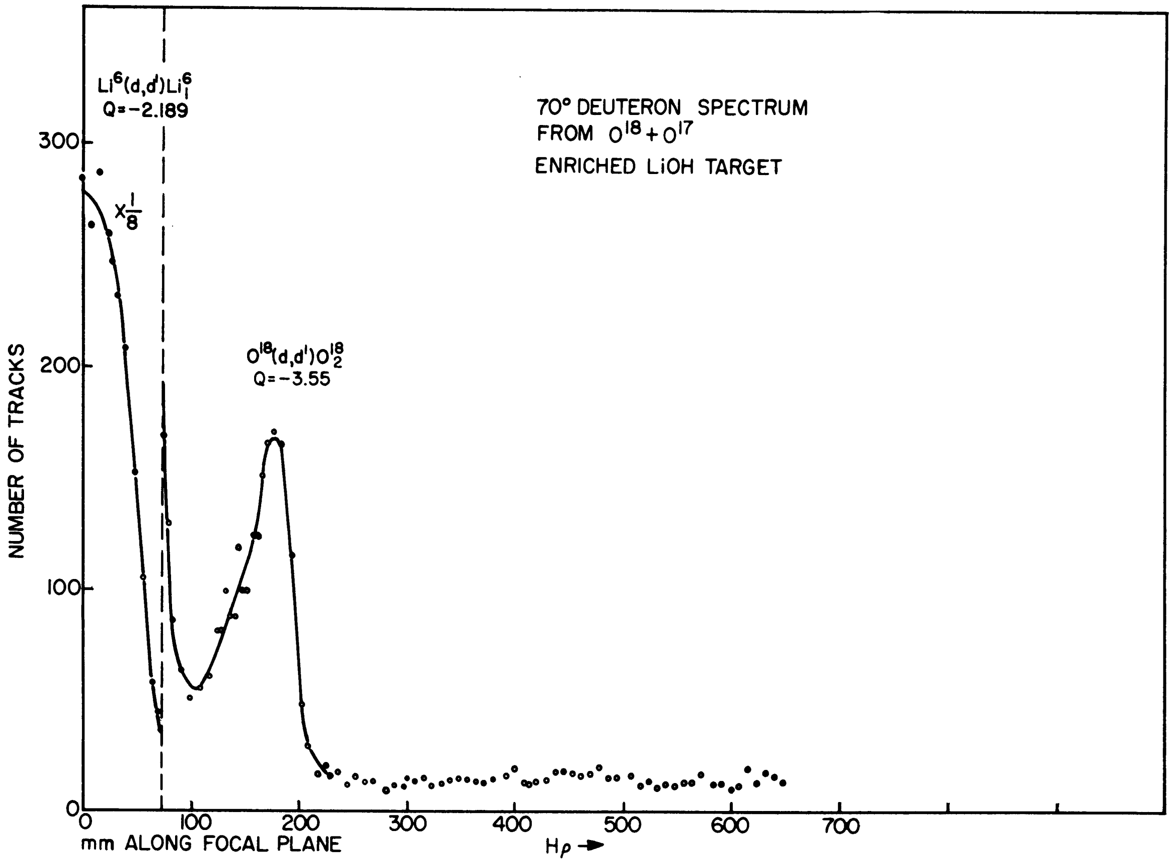
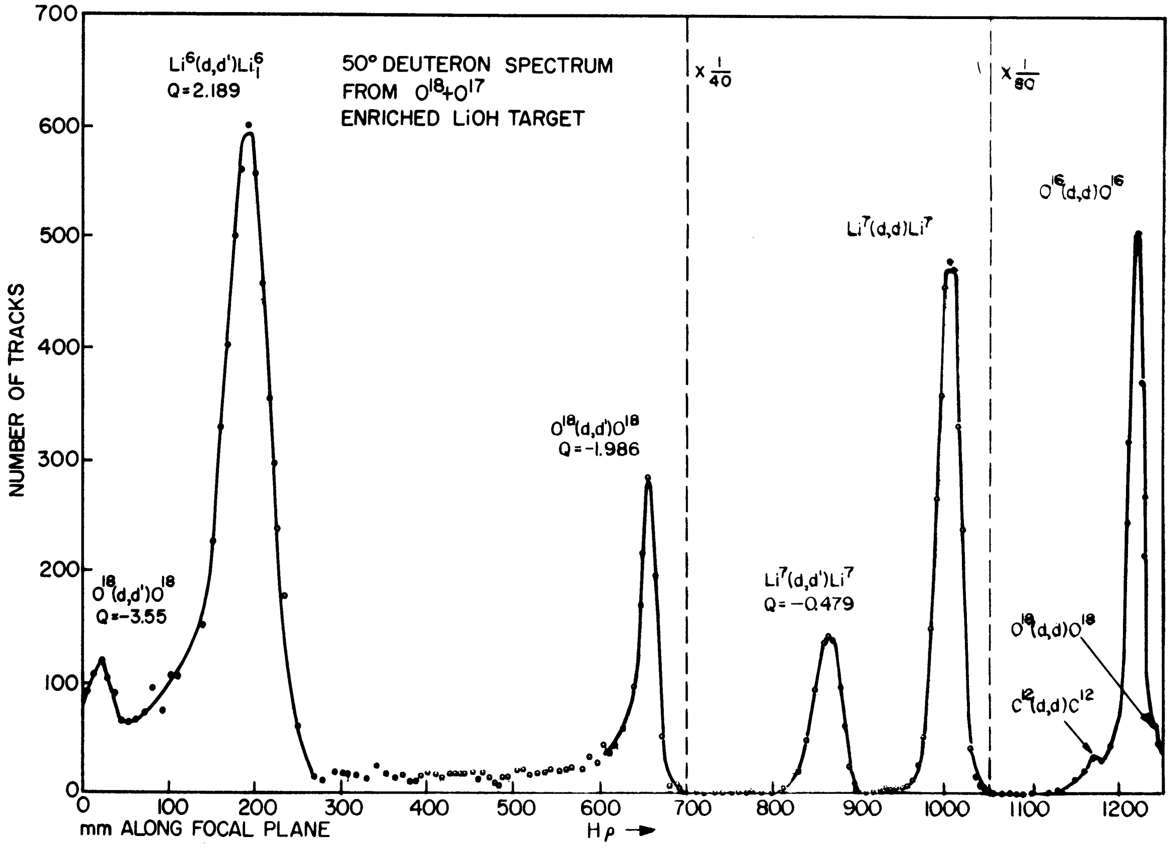

O17(d,p)O18 1
Q=3.835
Li6(d,p)Li
Q=4.553
Li6(d,p)Li7
Q=5.028
30° PROTON FROM O17+O18
ENRICHED LiOH TARGET
x 1/8
NUMBER OF TRACKS
mm ALONG FOCAL PLANE
Hρ

Fig. 3



70° DEUTERON SPECTRUM
FROM O18 + O17
ENRICHED LiOH TARGET
Li6(d,d')Li61
Q=-2.189
X 1/8
O18(d,d')O182
Q=-3.55
NUMBER OF TRACKS
mm ALONG FOCAL PLANE
Hρ →



50° DEUTERON SPECTRUM
FROM O18+O17
ENRICHED LiOH TARGET
Li6(d,d')Li61
Q=2.189
O18(d,d')O18
Q=-3.55
O18(d,d')O18
Q=-1.986
x 1/40
Li7(d,d')Li7
Q=-0.479
Li7(d,d)Li7
x 1/80
O16(d,d)O16
O18(d,d)O18
C12(d,d)C12
NUMBER OF TRACKS
mm ALONG FOCAL PLANE
Hρ →

Fig. 4

than the ground state Q for both $O^{18}(d,p)O^{19}$ and $O^{16}(d,p)O^{17}$. Therefore, the level is assigned with certainty to O^{18}.

The measurements have served as a good test of the capabilities of the medium-resolution instrumentation, and have made clear two or three improvements needed for convenient and accurate energy measurements with the system. In this experiment, an unknown Q was measured to ± 15 kev. We are confident that the error can be reduced to ± 5 kev.

D. NEUTRON SPECTROMETRY

1. Time-of-Flight Spectrometer.—The characteristics of the fast-neutron spectrometer have been determined by measurements of gamma-ray flight times and with neutrons from a thick beryllium target. The measurements indicate that the deuteron pulse width from cyclotron is less than 5×10^{-9} seconds, the time resolution of the chronotron coincidence circuit is 4×10^{-10} seconds, and the optimum resolution in energy, using a 15-meter flight path, is 4% for 20-mev neutrons and 0.9% for neutrons of one mev.

The neutron spectrum obtained from the (d,n) reaction using a thick beryllium target and a relatively short flight path of 5.3 meters is shown in Fig. 5. The identification of the two sharp groups at 5.8 and 3.8 mev, respectively, is uncertain. (They are not due to pecularities of the instrument but probably are due to γ-rays.)

As a further test of the instrument, the neutrons from the reaction $O^{16}(d,n)F^{17}$ were measured at an angle of 25° with respect to the deuteron beam over a flight path of 5.3 meters, using a 150-kev-thick PbO_2 target. The spectrum is shown in Fig. 6. Of particular interest is the low-energy region, which shows the fifth and part of the sixth excited states of F^{17}. Much more data on the high-energy region is now being analyzed.

An undesirable feature of the instrument in its present state is the method of recording data. The chronotron pattern is displayed on an oscilloscope and the trace photographed on 35-mm film. The flight time for each individual neutron detected must be determined by measurement of the trace on the film. This process is slow and severely limits the amount of data that can be analyzed. A system for recording data automatically is being constructed and, while it will speed up considerably the measurement of neutron flight times and thus make feasible the measurement of (d,n) angular distributions, it undoubtedly will mean some sacrifice of resolution.

One of the distinct advantages of the neutron spectrometer is its ability to measure neutron groups arising from levels just below the threshold for neutron capture. This region cannot be reached by neutron-scattering and the usual techniques used for (d,n) reaction studies have too poor resolution.

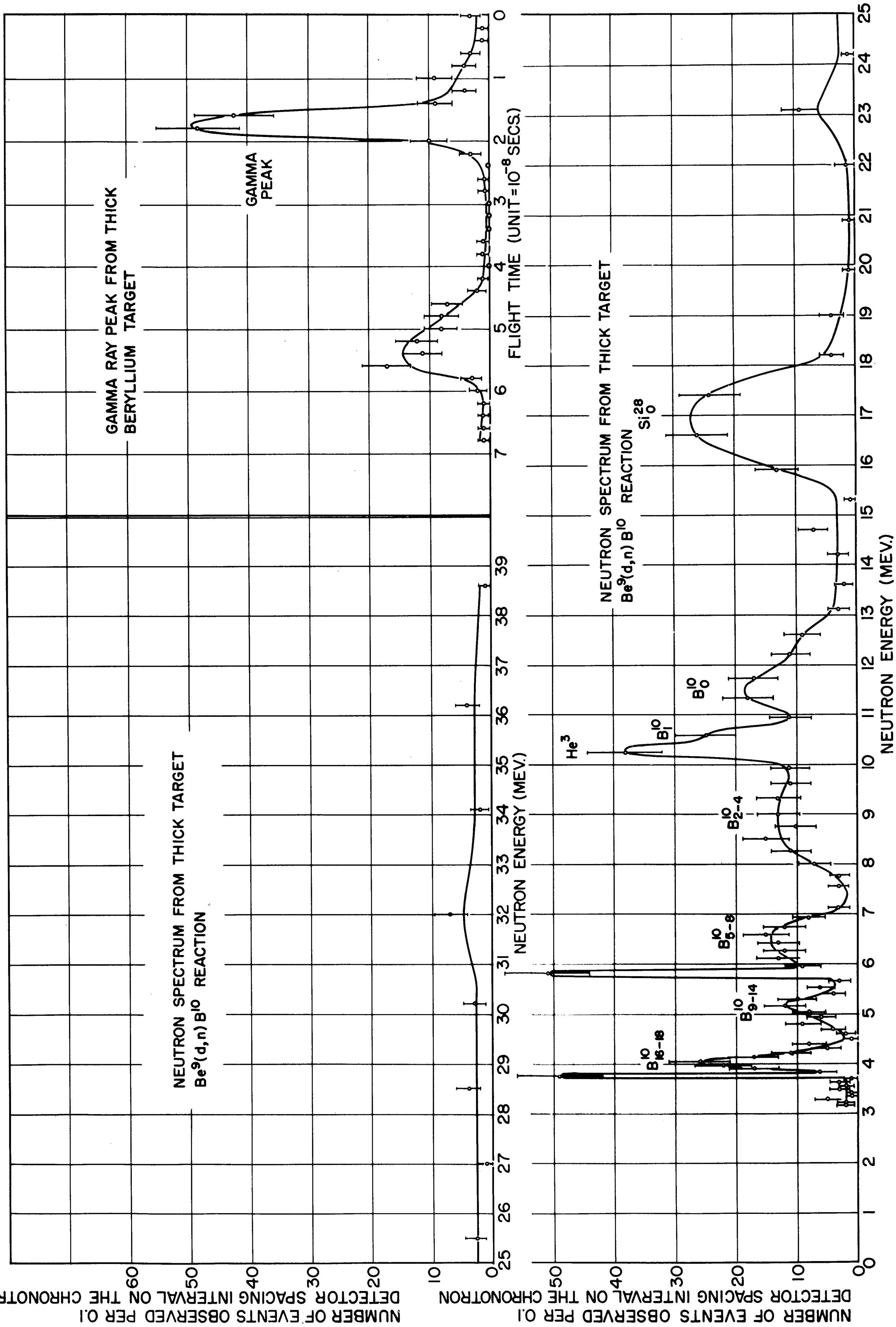
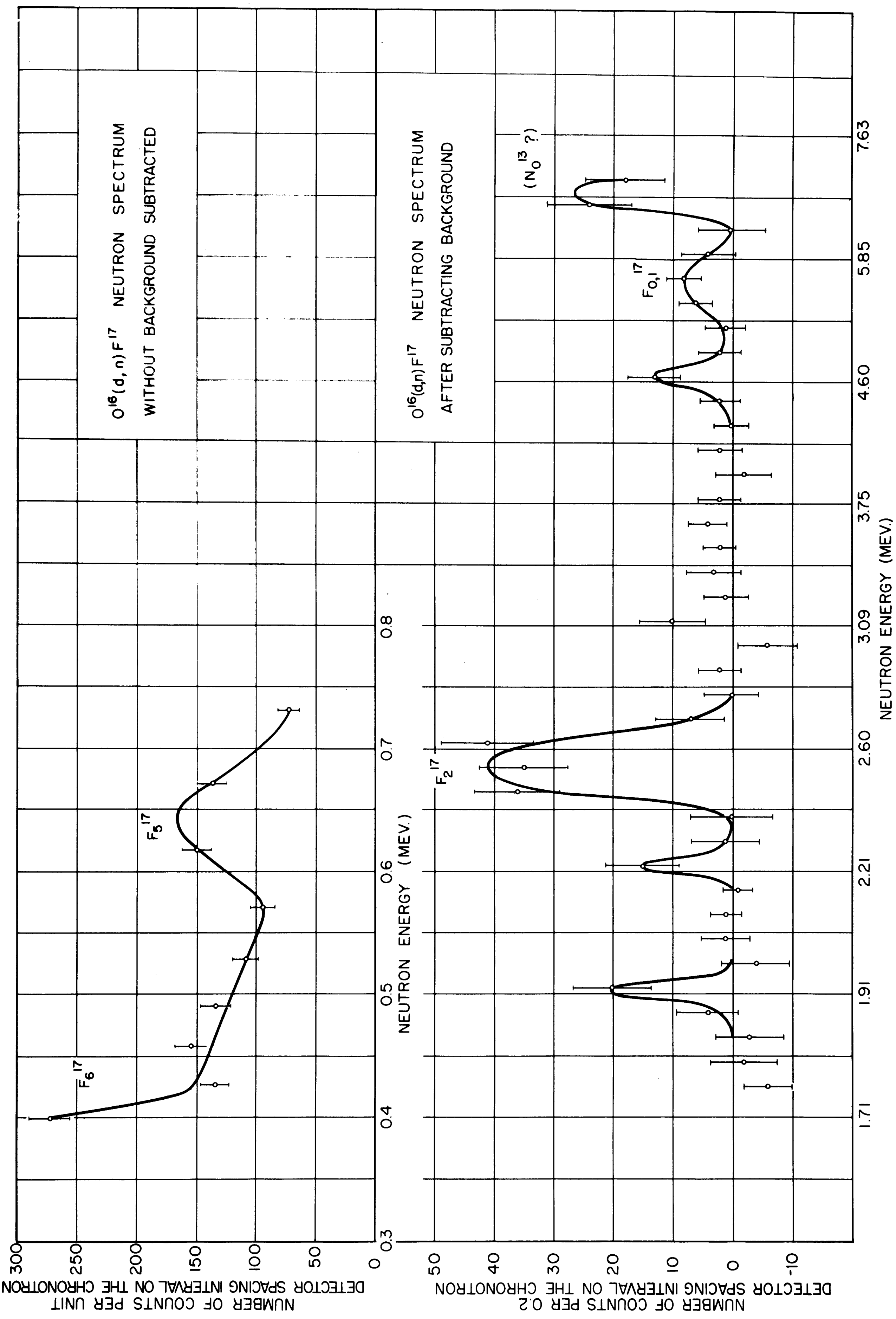

GAMMA RAY PEAK FROM THICK BERYLLIUM TARGET
GAMMA PEAK
FLIGHT TIME (UNIT = 10^-8 SECS.)
NEUTRON SPECTRUM FROM THICK TARGET Be9(d,n)B10 REACTION
NEUTRON ENERGY (MEV.)
NEUTRON SPECTRUM FROM THICK TARGET Be9(d,n)B10 REACTION
He3
B10 1
B10 0
Si28 0
B10 2-4
B10 5-8
B10 9-14
B10 15-18
NEUTRON ENERGY (MEV.)
NUMBER OF EVENTS OBSERVED PER 0.1 DETECTOR SPACING INTERVAL ON THE CHRONOTRON
NUMBER OF EVENTS OBSERVED PER 0.1 DETECTOR SPACING INTERVAL ON THE CHRONOTRON

Fig. 5



O16(d,n)F17 NEUTRON SPECTRUM
WITHOUT BACKGROUND SUBTRACTED
O16(d,n)F17 NEUTRON SPECTRUM
AFTER SUBTRACTING BACKGROUND
(N13 0 ?)
F17 0,1
F17 2
F17 5
F17 6
NEUTRON ENERGY (MEV.)
0.3
0.4
0.5
0.6
0.7
0.8
NEUTRON ENERGY (MEV.)
1.71
1.91
2.21
2.60
3.09
3.75
4.60
5.85
7.63
NUMBER OF COUNTS PER UNIT
DETECTOR SPACING INTERVAL ON THE CHRONOTRON
300
250
200
150
100
50
0
NUMBER OF COUNTS PER 0.2
DETECTOR SPACING INTERVAL ON THE CHRONOTRON
50
40
30
20
10
0
-10

Fig. 6

2. Nuclear Recoil Spectrometry.—An attempt is being made to measure neutron energy and angular distributions from (d,n) reactions by focusing the recoil nuclei by means of the analyzer magnet. A double proportional counter of somewhat unusual design has been constructed for detection of the recoils. The counter uses the standard mixture of 96% A + 4% CO_2 but at an absolute pressure of only 2 cm of Hg. The central wire is 1/16-in. in diameter, so that the strong-field region near the wire extends over the same number of electron-collision mean free paths as it does in a conventional counter operating at a higher pressure. The window is a 30-μg/cm^2 Formvar film, supported by a grid. In tests of the analyzer magnet, the counter has been used with the alpha particles from polonium as a source, but detection of recoils has not yet been tried.

E. POLARIZATION IN THE (d,p) REACTION

The experiment to determine the polarization of the outgoing proton in the (d,p) reaction (1954 Progress Report) has given no definite result as yet. To date, it has been established that the deuteron beam from the cyclotron is less than 1% polarized. (This result was fully expected.) The asymmetry in the scattering introduced by the experimental apparatus is less than 1%. The measurements are held up at present because of the high ratio of the background to true counting rage after the second scattering. A pair of strong-focusing alternate-gradient magnets, which are under construction, will be placed between the first and second scatterers for the purpose of increasing the solid angle seen by the second scatterer, and to allow space between the two scatterers for effective shielding. It is expected that the background will be reduced by a factor of 50 to 100 and thus permit detection of the polarization if it does exist.

The measurements to date have been made with protons from the C^{12} $(d,p)C^{13}$ ground state using the P3/2 level in helium as the polarization detector.

F. (d,α) REACTIONS IN MIDDLE-WEIGHT NUCLEI

During the period from August, 1954 to July, 1955 some 33 bombardments were made for the chemistry group under the direction W. W. Meinke. In addition, approximately 10 days were devoted to setting up and calibrating the instrumentation for the deuteron bombardments.

Absolute cross section for the formation of several radio-nuclides at well-defined deuteron bombarding energies have been measured. The elements irradiated include cadmium, sulfur, titanium, magnesium, phosphorus, tin, vanadium, aluminum, and zirconium. Details of this work will be given in Progress Report No. 4 of Project No. 7, of AEC Contract AT(11-1)-70.

V. THE THEORETICAL PROGRAM

A. STRIPPING THEORY

1. Extension of the Butler Theory.—The Butler formulation of the stripping theory is being extended to include Coulomb effects in an essentially exact manner by modifying the usual binary-rearrangement-collision theory to include the Coulomb force between the centers-of-mass of the colliding systems. The incident wave has been improved by a representation of a polarized deuteron as a "displaced charge cloud" of the proton with respect to the neutron. The latter modification alone produces a Coulomb correction to the simple theory. Other effects which are to be included are the proton-nuclear interaction, the neutron-proton interaction inside the nucleus, and the proton polarization by spin-orbit interaction with nucleus.

The complete treatment of these effects requires the use of the high-speed Michigan Digital Automatic Computer.

2. The Coulomb Effect.—A simple and approximate calculation of the effect of the Coulomb field on the stripped proton in the (d,p) reaction was carried out. In a typical case the theoretical absolute cross section is reduced by a factor three, and the nuclear radius required to fit the experimental angular distribution reduced by 20%. The reduction in cross section improves the agreement between theory and experiment, and the smaller radius required is in better agreement with values obtained from neutron-scattering data. The calculations will be outmoded by the more elaborate treatment mentioned above, and may not be published.

3. Stripping Nomographs.—Nomographs were constructed to facilitate the plotting of the theoretical stripping angular distributions for ℓ-values from zero to five. A description of the nomograph was published* and a complete set of the graphs is being made available to those interested.

4. Survey of Stripping Data.—A survey is being made of all available data on angular distributions from the stripping reaction. Theoretical distributions are being calculated to give a uniform treatment of the data. Systematic deviations between the extended Butler theory and experiment will be studied, in the hope that a better understanding of nuclear structure can be obtained.

*Rev. Sci. Inst., 26, 400 (1955).

B. TWO NUCLEON CONFIGURATIONS IN j-j COUPLING WITH TENSOR FORCES

As part of a program of interpretation of the experimental results in O^{18}, the diagonal matrix elements of the tensor force were calculated for the configurations $(d5/2)^2(d5/2\ d3/2)$, $(d5/2\ s1/2)$ $(d3/2\ s1/2)$, and $(d3/2)^2$. The first-order interaction energies were expressed in terms of the integrals I_ℓ of Talmi for harmonic oscillator wave functions, and explicitly calculated for several assumed interaction potentials.

A principal tendency of the addition of the tensor force in O^{18}, while still preserving the properties of the deuteron, is a reduction in overall binding. In the $(d5/2)^2$ configuration, the tensor force acting alone will, for some force ranges, invert the J = 2 and J = 4 levels. Off-diagonal elements are needed for accurate comparison with experiments. A preliminary report of this work was made at the Chicago meeting of the American Physical Society.*

VI. CONFERENCE ON NUCLEAR STRUCTURE

At the instigation of the cyclotron group, a conference on the problems of nuclear structure was held on the Michigan campus during the week of June 27, 1955. The two short and informal meetings held each day served as focuses for individual discussions at other times among the approximately seventy physicists in attendance. Support for the conference was derived jointly from the summer symposium fund of the University of Michigan and from the National Science Foundation.

*Phys. Rev., 98, 235 (1955).