

THE STRUCTURE OF O¹⁹

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CHAPTER I

INTRODUCTION

Evolution of the individual particle model

Despite the smooth variation of many nuclear properties with N and Z , a large body of experimental evidence (1) indicates abrupt discontinuities in this average behavior at specific (magic) neutron and proton numbers, namely, N or Z equal to: 2, 8, 20, 28, 50, 82, and 126. Further, the properties of magic nuclei (nuclei possessing a magic number of protons or neutrons or both, such as the doubly magic: ${}^4_2\text{He}$, ${}^{16}_8\text{O}$, ${}^{208}_{82}\text{Pb}$, ...) suggest that in nuclear matter the nucleons are "arranged" in shells similar to the electronic shells of the atom and that magic nuclei, like the noble gases, represent shell closures.

Early theoretical attempts to derive these magic numbers led only to limited agreement. In 1949, however, Mayer (2) and, independently, Jensen and co-workers (3) proposed a strong spin-orbit interaction term in the nuclear Hamiltonian (in addition to a distorted harmonic oscillator well) and were able to produce shell closures at all the magic numbers.

Subsequently, Mayer (4) prescribed a set of supplementary coupling rules which resulted in the extreme single-particle shell model. In this model the ground state properties of odd-A nuclei were regarded as arising from the motion of the last odd nucleon (either a proton or neutron) in the spherically symmetric potential produced by the remaining even (even N and even Z) number of nucleons which coupled, in pairs, to a spin zero core.

This original, extreme single-particle form of the shell model was remarkably successful in predicting the spins and many other properties of nuclear ground states. But, except for rare instances, it was not capable of dealing with excited states where the Mayer coupling rules break down. Experiments indicated—at least for light nuclei and in regions near closed shells—that the properties of excited states originated mainly in the interdependent motions, limited by the exclusion principle, of all nucleons outside the spinless core of closed shells. This refinement has led to the individual particle model of the nucleus.

In this model the individual nucleons—usually those outside the core—are assumed to interact in lowest order only with the central field of the nucleus. Hence, the state of each nucleon is represented by a single-particle wave function appropriate to the potential (normally an oscillator or square well) chosen to describe

the central interaction. These single-particle wave functions are then coupled together into the properly antisymmetrized wave functions which characterize those states of the system that can be constructed from the individual particle states. Finally, the energy levels and the composition of the state wave functions are evaluated by considering the interparticle forces (possessing exchange character) acting between pairs of nucleons and the effective nuclear spin-orbit force acting on the individual nucleons as a perturbation.

Two general features have become apparent from several of the detailed calculations (5, 6, 7) that have been carried out using this model. First, the intermediate coupling scheme—in which the interparticle and nuclear spin-orbit interactions are of comparable strength—yields better agreement with experiment than either the extreme LS-coupling approximation (nuclear spin-orbit interaction neglected) or the extreme jj-coupling approximation (interparticle interaction neglected). Second, correct level sequences are obtained only when the wave functions characterizing the states of the system are constructed from appropriate configuration-mixed, single-particle wave functions; that is, when the states are considered to be in configuration interaction.

This model shows promise of being able to predict with fair accuracy many of the properties of nuclear excited states. It is

hoped that as more data are accumulated for light nuclei near closed shells the model calculations can be extended sufficiently (by including, for example, the effects of core excitation) to produce a more comprehensive agreement with experiment.

(d,p) Stripping in nuclear spectroscopy

Shortly after the extreme single-particle shell model was proposed, Butler (8) gave an analysis of the angular distribution of protons from the (d,p) stripping reaction. Subsequently, a series of (d,p) experiments were performed which confirmed many shell model predictions, particularly in the case of one stringent test which involved the ground state of Cl^{36} .

For this nucleus, spin and parity selection rules allowed the stripped neutron to be captured with orbital angular momentum values of $l_n = 0, 2, 4$; the shell model, on the other hand, allowed only $l_n = 2$. Since the (d,p) transition rate for an $l_n = 0$ capture is approximately twenty times more intense than the rate for $l_n = 2$, the former, if present, would dominate the results. The $\text{Cl}^{35}(\text{d,p})\text{Cl}^{36}$ experimental results of King and Parkinson (9) clearly showed an $l_n = 2$ capture (with a few percent admixture of $l_n = 0$) and thus confirmed the shell model prediction.

This reaction continues to be of major importance in nuclear spectroscopy because of several desirable features. Since there is a third particle—the outgoing proton—to carry off excess energy, states of low excitation can be formed readily by a (d,p) reaction that are not reached by other reactions. Further, the analysis of the shape of proton angular distributions yields, in almost all cases, an unambiguous determination of the orbital angular momentum, l_n , carried into the nucleus by the stripped neutron. From this l_n value the parity of the final nuclear state can be determined directly if the parity of the initial (target) nucleus is known. Since l_n -odd indicates a parity change and l_n -even indicates no change in parity between the initial and final nuclear states. In addition, by taking into account the uncertainty of $\pm 1/2$ unit in the total spin angular momentum carried into the nucleus by the neutron ($j_n = l_n \pm 1/2$), the following limits can be placed on the spin of the final state: $|J_i - l_n - 1/2| \leq J_f \leq J_i + l_n + 1/2$, where J_i and J_f are the spins of the initial state and final state, respectively.

Thus, a Butler analysis of proton angular distributions from (d,p) stripping reactions can be used to predict the parities and, within limits, the spins of nuclear states. In addition, a comparison between observed transition rates and transition rates calculated from stripping theory (10) can be employed in certain cases to impose

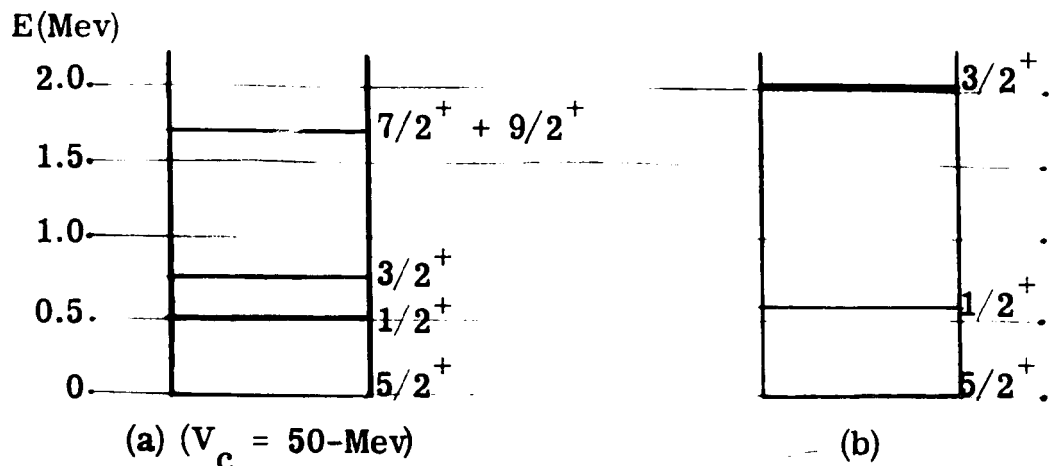
additional limits on spin assignments and to examine the composition of nuclear state wave functions.

Purposes of the investigation

Three states had been reported for the O^{19} nucleus prior to this investigation (11): a level, tentatively identified as the ground state, with a (d,p) Q-value of 1.730-Mev and two excited states at 0.096-Mev and 1.470-Mev excitation. Also, an assignment of $J^\pi = 1/2^+$ to the 1.470-Mev state had been made on the basis of several (d,p) angular distribution studies (12, 13).

In addition to these data, detailed theoretical calculations had been performed for the low-lying even parity states of mass 19 nuclei by Elliott and Flowers (5) and Redlich (6, 7). Their predictions of the low-lying level structure of O^{19} are summarized in Fig. I-1.

Fig. I-1. The level structure of O^{19} predicted by (a) Elliott and Flowers and (b) Redlich.



In addition, both gave percentage analyses of the wave functions into jj-coupled configurations for the $5/2^+$, $3/2^+$, and $1/2^+$ states.

The purposes of this investigation, in view of the existing data and theoretical predictions, were, therefore: first, to determine the parities and spins of the known states; second, to search for new states at higher excitation energy and, if found, to determine their parities and spins; and third, to compare the observed O^{19} level structure with theory.

CHAPTER II

EXPERIMENTAL CONSIDERATIONS

The experimental arrangement

As the introductory chapter has indicated, the deuteron induced $O^{18}(d,p)O^{19}$ stripping reaction was employed throughout this investigation of the level structure of O^{19} . The following experimental arrangement was used for this investigation and is illustrated in Fig. II-1.

The deuterons were accelerated to a nominal energy of 7.8-Mev by the 42" cyclotron. After being extracted from the cyclotron, the beam was energy analyzed and focused by means of the focusing magnet onto thin, O^{18} -enriched LiOH targets mounted in the scattering chamber. The magnetic field of the focusing magnet was adjusted to produce a deuteron beam energy of 7.775-Mev at the target (this adjustment technique is described in the following section).

The protons which resulted from the deuteron-induced reactions on O^{18} and other target nuclei were momentum analyzed by the high resolution magnetic analyzer which was positioned at the selected reaction angle. Kodak NTB and NTB-2 nuclear emulsion

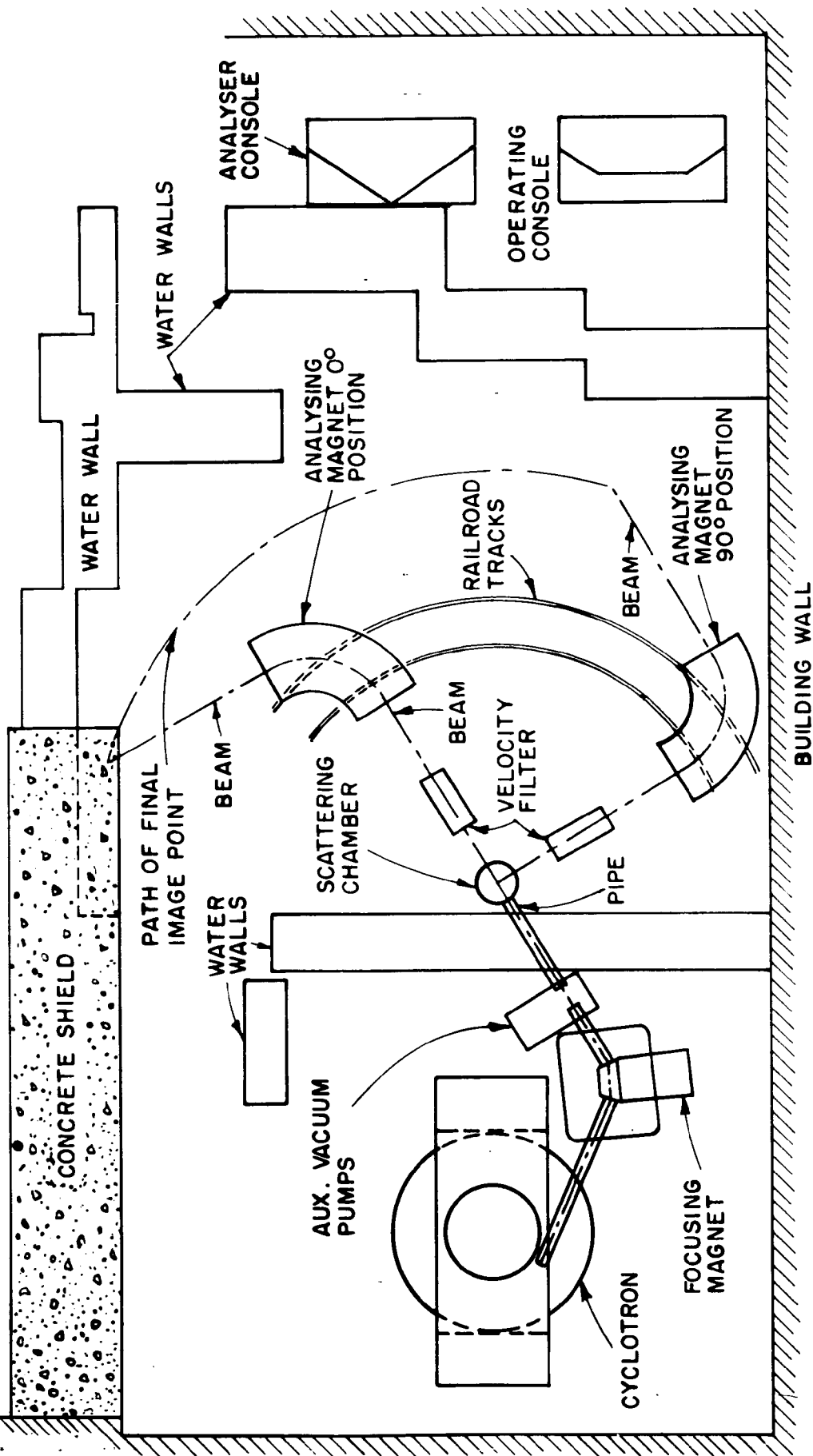


FIG. II-1. CYCLOTRON LAYOUT

plates were placed at the image plane of the analyzing magnet and used to detect these protons.

In some instances the velocity filter which is placed between the scattering chamber and the analyzing magnet was employed to prevent beam deuterons from entering and subsequently scattering through the analyzing magnet onto the nuclear emulsion plates.

Details of this general arrangement and of individual components are given elsewhere (14, 15).

Beam spot technique

A technique by which the beam energy is easily adjusted to a value of 7.775-Mev before each run was used throughout this investigation.

In this arrangement, the deuteron beam is sent directly to the image plane of the analyzing magnet positioned at 0° . At the image plane the beam strikes the phosphor-coated face of a glass plate and produces a spot of light (the beam spot) which is observed from outside the water walls by means of a telescope and suitably arranged mirrors. With the magnetic field of the analyzing magnet set to center 7.775-Mev deuterons in the image plane, the focusing magnet is adjusted to center the beam spot in the analyzer image plane. This adjustment, therefore, fixes the beam energy at the value of 7.775-Mev.

This particular value of 7.775 ± 0.015 -Mev (16) was determined initially by a three-stage process. First, the focusing magnet was adjusted to produce maximum beam intensity at the target. Second, with the analyzing magnet positioned at 0° , the analyzer magnetic field was adjusted to center the beam spot. Third, the beam energy for this optimal beam intensity was determined by using a method, similar to that described in (15), which is largely independent of the magnetic analyzer calibration.

Target preparation

The preparation of the thin LiOH targets followed the procedure described by Bilaniuk (14, 17). Lithium metal was evaporated under vacuum onto a double thickness of gold leaf mounted on a target frame. After the proper amount of lithium had been deposited on the leaf, O^{18} -enriched water was slowly admitted to the system to form the LiOH through the $2Li + 2H_2O \longrightarrow 2LiOH + H_2$ reaction. (This 80 percent O^{18} , enriched water was procured from the Atomic Energy Research Establishment, Harwell.)

Each target was tested for O^{18} content and thickness before being used. This was necessary for three reasons: First, the appropriate thickness of the evaporated lithium could be judged only from appearance and evaporation time. Second, a high initial O^{18}

content depended upon an adequate exposure of the freshly evaporated lithium to the water vapor; this also could be judged only on the basis of appearance and exposure time. If the exposure were too short, the lithium was incompletely hydroxidized; if, on the other hand, the exposure were too long, target nonuniformities developed. Third, a factor which affected the initial O^{18} content but which was not connected directly with the target manufacture was the dilution of the O^{18} upon exposure of targets to air. This dilution which results from an O^{18} - O^{16} isotopic exchange reaction did not take place so rapidly as had been expected (14, 18). (A vacuum failure, for example, exposed one target to air for ~ 10 minutes with only a 25 percent loss of the known O^{18} content.) Nevertheless, the dilution was significant enough to demand rapid transfers of the targets from the evaporating system into the scattering chamber.

The targets were tested by obtaining a 30° spectrum of the proton groups associated with the ground states of O^{19} and O^{17} . An intensity ratio of 1:4 was adopted as the minimum O^{18} content criterion; the satisfactory resolution of these two groups (separated by 0.165-Mev) and group widths < 0.050 -Mev at half-maximum height were used as the target thickness criteria. The target uniformity was judged on the basis of the symmetrical appearance of the groups.

Velocity filtering

Normally, sufficient absorber (Al or Pb) is placed over the nuclear track plates so that deuterons which have entered and scattered through the analyzing magnet are prevented from penetrating the emulsion. At reaction proton energies < 6.5 -Mev and at low reaction angles, however, this use of absorber must be supplemented by an additional discrimination technique because absorber that is sufficiently thick to prevent a deep penetration of the scattered deuterons also significantly shortens the range of the reaction protons in the emulsion. The occurrence of these short proton tracks mixed with short deuteron tracks necessitates time-consuming track-analysis scanning before meaningful reaction proton spectra can be obtained.

The additional discrimination against the unwanted deuterons is provided by the newly constructed velocity filter (19). This combination of crossed electric and magnetic fields is adjusted to permit only those particles having a velocity equal to the velocity of a reaction proton of the desired energy to pass undeflected through the filter and to enter the magnetic analyzer. Particles having different velocities are deflected in the vertical plane and are subsequently stopped by lead faced slits at the entrance to the analyzer magnet.

Because the deuteron velocity is equal to the proton velocity at a deuteron energy of twice the proton energy, the velocity filter cannot produce large deuteron deflections when reaction proton energies of approximately one-half to three-quarters of the deuteron beam energy are being investigated. In this energy region around 5-Mev the vertical slits were closed down from the normal separation of 1.3'' to a 0.3'' separation in order to utilize the modest vertical deuteron deflections of $+1/2$ cm at the analyzer entrance. Further slit reduction would, of course, have made more effective use of the velocity filter, as reference to Fig. 2 of (19) will show, but the consequent decrease in the intensity of reaction protons detected at the analyzer image plane would have required prohibitively long bombardments.

This use of the velocity filter reduced the deuteron background to a tractable scanning level for all the low angle angular distribution plates exposed in this investigation.

Contaminant protons from carbon

A severe proton background encountered at several low reaction angle exposures was identified with the (d,p) reaction on carbon contained in pump oil that had accumulated on the walls of the pipe leading into the scattering chamber.

This identification was suggested initially by low angle spectra which showed an intense, degraded energy tail-structure associated only with the C_3^{13} proton group; neighboring proton groups were shaped normally.

In order to eliminate this pump oil carbon as a source of background protons, five tungsten apertures were inserted at 3'' intervals in the pipe to shield the walls from the deuteron beam. This reduced the background sufficiently to permit angular distribution measurements at the forward angles. The fact that the background was not completely eliminated (see Fig. IV-2), however, suggests the possible existence of additional sources of $C^{12}(d,p)$ -protons somewhere in the ductwork of the system.

CHAPTER III

THE MACHINE SCANNER

The scanning problem

The nuclear emulsion has been chosen as the detector of reaction particles in many nuclear spectroscopic experiments because of its desirable properties of continuous sensitivity, excellent resolution capabilities, and the fact that the data are permanently recorded in the emulsion after development. The simplicity with which emulsions are employed during the course of an experiment has been nearly vitiated, however, by the necessity of expensive and time-consuming microscopic scanning by human observers.

In nuclear spectroscopic investigations employing the University of Michigan 42" cyclotron, the (d,p) stripping reaction protons are momentum analyzed by the magnetic analyzer (of known field and dispersion) and recorded by 1" $\times$ 10" nuclear emulsion plates (100 μ emulsion thickness) carefully positioned at the analyzer image plane. After the plates are developed, the proton tracks are counted by a field-by-field analysis (see Appendix A) in 1/2-mm-wide swaths across the 1" dimension of the plates. (A magnification of $\sim 200\times$

is normally employed.) The reaction proton energy spectrum contained in a given plate is obtained by plotting the number of proton tracks per swath as a function of the swath position along the 10'' dimension of the plate.

As an example of the magnitude of the scanning problem normally encountered, the second survey in this investigation of O^{19} involved the exposure of thirty-two of these 1'' $\times$ 10'' plates in a 24-hour cyclotron run. This necessitated the examination of approximately 400,000 fields (equivalent to 50-60 days of scanning by a human observer) to acquire the data contained in these plates. At the time of this survey, several similar investigations involving a comparable number of plates were also in progress.

The machine scanner which scanned twenty-eight of these thirty-two plates at the rate of one per 90 minutes will be described in this chapter.

Outline of scanner operation

The machine scanner operation is divided into three major categories: the automated motion of the nuclear emulsion plate under the objective lens of the microscope in a selected precision pattern of scanning swaths; the high speed recognition of tracks in the individual fields of view which compose these scanning swaths; and the

automatic recording of the track count as a function of swath position in the nuclear emulsion plate.

Nuclear emulsion plate motion

The mechanics responsible for the motion of the nuclear plate is illustrated in Fig. III-1.

The plate rests in a channel provided in the microscope stage and is moved under the oil-immersion lens of the microscope by two electric motors which are programmed to produce the desired pattern of scanning swaths. The synchronous motor at the left of Fig. III-1, which is coupled to the microscope stage by a precision screw and nut arrangement, alternately pushes and pulls the stage and is responsible for the constant speed, back-and-forth motion of the plate along the scanning swaths. The motor in the foreground of Fig. III-1 pushes the plate a selected distance along the channel at the completion of each swath and is responsible for the transition from one swath to another.

These motions of the nuclear plate are monitored by a number of microswitches which are placed at strategic locations throughout the mechanical set-up. (The tops of the two cam-operated microswitches associated with the motor in the foreground of Fig. III-1 are visible on the microscope side of the motor mount.) The



Figure III-1. The mechanics and optics of the scanner.

electrical information derived from the opening and closing of these microswitches is fed to a group of relays (not shown) whose function is to control the operation of the motors and the electromechanical brakes attached to the motors according to a preselected schedule.

Track recognition

The problem of high-speed track recognition has been met by the use of the following connected systems:

1. The television system whose function is to convert optical information; namely, the brightness at each point in the emulsion scene, into electrical information as a function of time.
2. The width discriminating system which examines the output of the television system and rejects artifacts (such as "blobs") that are easily distinguished from tracks.
3. The track analysis system whose function is to sift the output of the width discriminator for tracks and to mark off the sifted tracks into segments.
4. The spot read-out system which integrates the marked track segments output of the track analysis system to yield a single count for a track that is arbitrarily long, provided the track is greater than some minimum length.

The television system.—The microscope is arranged to project the magnified image of an emulsion scene onto the photosurface of a 5820 Image Orthicon, the image pick-up tube in a standard television camera. (The front end of the camera can be seen at

the upper right in Fig. III-1). The complete television system employed (20) consists of: the camera chain (the camera, camera control, and power supply) which converts the brightness at each point in the emulsion scene into electrical information expressed as a function of time; a synchronizing generator which generates the appropriate timing pulses for the camera chain and monitor; and a studio monitor for viewing purposes.

A property of the television system that will be of importance in subsequent discussion is the ability of the Image Orthicon to store an undistorted image of the emulsion scene until this image is wiped clean by the television scanning process and, as a result of this, its ability to integrate the intensities of distinct pulses of light which fall on the same area of the photosurface.

The typical emulsion scene to be analyzed contains, in addition to the tracks (linear arrays of developed silver grains), individual background grains, "blobs" (clusters of background grains), and other artifacts. These features are illustrated in Fig. III-2 which is a photograph of a televised emulsion scene. (The diagonal stripe is due to the motion of the focal plane shutter of the camera taking the photograph.) Examination of this photograph shows that the upper and lower ends of the track and many of the background grains are blurred. This blurring indicates that these components



Figure III-2.—Televised emulsion scene.

of the emulsion scene are outside the limited slice of the emulsion maintained in sharp focus by the microscope.

The optical information contained in this typical emulsion scene was converted into electrical information (the video) by means of a rapid point-by-point scan of the scene along a grid of horizontal scan lines in one sixtieth of a second. (This grid of horizontal scan lines is called the scanning raster and is visible in Fig. III-2.)

The video output of the television system contains the following information that is employed by the width discriminating system: the signal level changes abruptly when the television scanning element moves from a "white" region (no developed silver grain) to a "black" region (presence of a developed silver grain in focus) and vice versa; the amplitude of this signal is proportional to the "blackness" (up to saturation); and the width of this video pulse is a measure of the spatial extent of the "black" region.

Width discriminating system.—The width discrimination system (21) is designed to analyze the video output from the television system and reject all pulses whose widths are greater than the pulse widths associated with normal, reasonably black, developed grains. This eliminates "blobs" and other artifacts of abnormal

spatial extent from further consideration. Pulses of acceptable widths are replaced by output pulses of nearly uniform amplitude and width.

Fig. III-3 is a photograph of a televised scene containing a track, the usual complement of background grains, and a "blob." The white spots to the right of the track and the background grains are the uniform output pulses from the width discriminating system which have been electronically mixed with the video output of the television system. The displacement of these pulses to the right of the video pulses is a measure of the time required by the system to make a width "decision."

The "blob," except for regions of fine structure, has been completely eliminated. Further, the fact that there exists no intrinsic difference between a video pulse resulting from a background grain and one associated with a track grain is emphasized by the behavior of this system.

Track analysis system.—Background grains are recognized as such by a human observer because there exists no ordering of their distribution in the emulsion scene; a track, however, is an ordered linear array of grains.



Figure III-3.—Width discriminating system output.

Because the television system converts a spatial distribution of optical information into a temporal distribution of electrical information, the above statement can be immediately translated into the following machine language: The pulses associated with background grains are randomly distributed in time; the pulses associated with track grains are distributed in an orderly fashion in time. In particular, a vertical track (one that is oriented at a 90° angle with respect to the scanning raster) is represented by a sequence of pulses which are uniformly separated from each other by the amount of time necessary for the television scanning element to go from a point on a given raster line to a point directly below on the next raster line. (This time interval is precisely $63.5 \mu\text{sec.}$) Tracks that are not vertical will also be represented by a sequence of uniformly spaced pulses. In this case, the pulses are separated from each other by a time interval that is either greater or less than that of the vertical track depending on the sign of the track angle relative to the vertical.

The track analysis system exploits this distinction between background grain pulses and track grain pulses by testing each width discriminating system output pulse for a possible correlation with a subsequent pulse. The design of this system is such that a moderately curved track oriented within $\pm 45^\circ$ relative to the

vertical leads to a series of successful pulse correlations over the in-focus length of the track.

The operation of the system is, simply, that if a successful correlation between two pulses is established, the number 2 is stored. This then tests for a successful correlation with a third pulse; if this correlation is established, the number 3 is stored which in turn tests for number 4, et cetera. The net result of this testing procedure is that the system yields a track segment pulse after the first sixteen successful correlations and a track segment pulse for each group of eight successful correlations thereafter. (Additional details of the operation of this system are given in Appendix B.)

Fig. III-4 is a photograph of a televised emulsion scene containing five tracks. The wide, white lines to the right of each track are the track segment pulses from the track analysis system which have been electronically mixed with the video output of the television system.

Spot read-out system.—Because tracks are not necessarily uniformly oriented in the emulsion, their in-focus lengths, and therefore, the numbers of track segment pulses associated with these in-focus lengths, are variable quantities. The determination of the

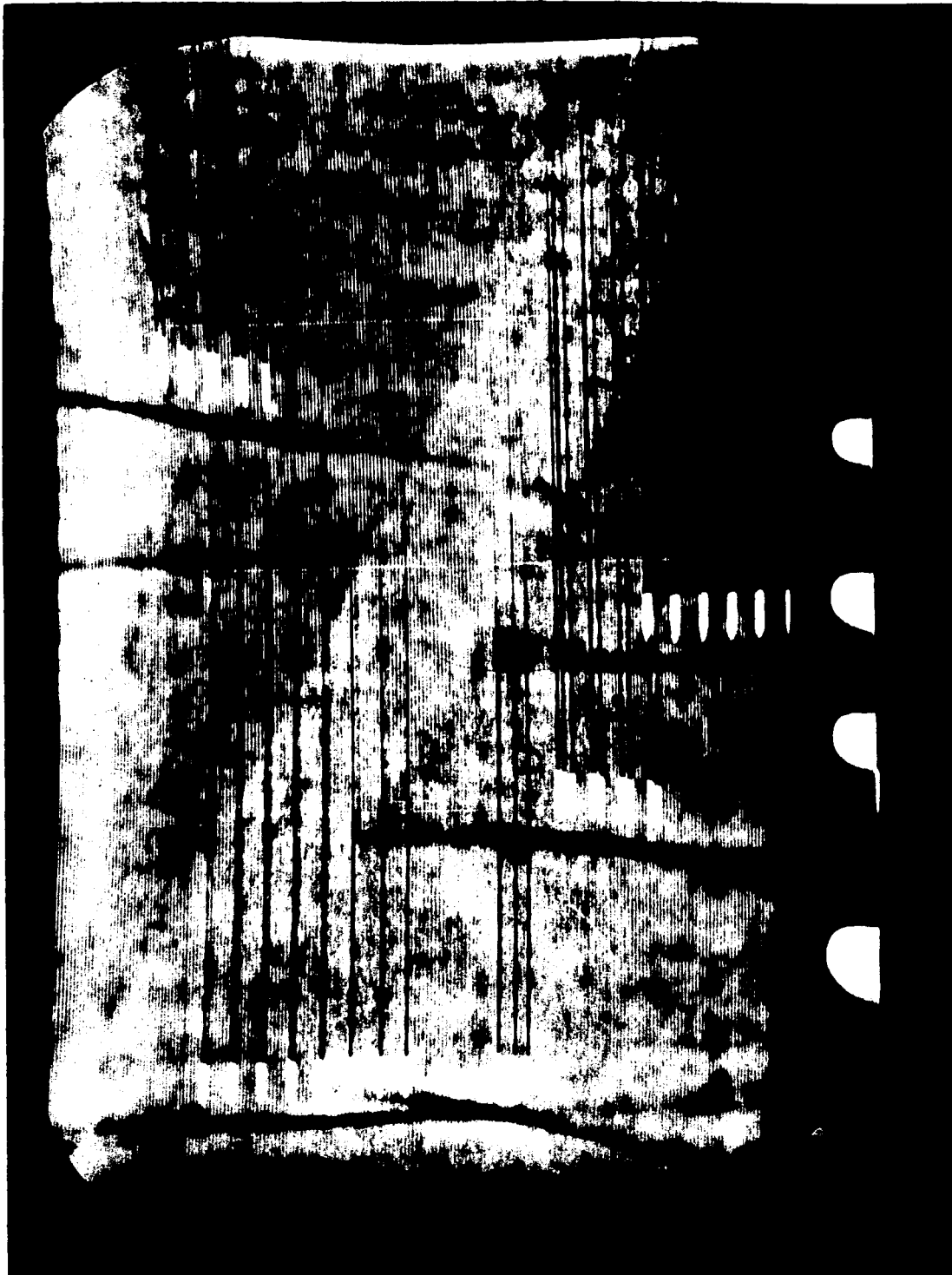


Figure III-4.—Track analysis system and spot read-out system output.

number of tracks responsible for the track segment pulse output of the track analysis system should be independent, therefore, of the number of track segment pulses associated with each track. Such a determination is complicated by the fact, however, that the track segment pulses associated with each track are interleaved in time.

The spot read-out system uses an auxiliary oscilloscope to sort out these interleaved track segment pulses and associate them with the appropriate tracks and it uses the Image Orthicon to examine each track in a manner that is independent of the track's associated track segment pulses. This is arranged in the following way.

Upon command of a track segment pulse, a unit intensity light spot is produced by the auxiliary oscilloscope whose normally darkened trace is swept synchronously with the scanning element in the television system. This light spot is projected onto the bottom portion of the Image Orthicon photosurface, which is masked off from the emulsion scene, and illuminates an area at that horizontal position along a particular raster line appropriate to the horizontal position of the command track segment pulse along its raster line. Subsequent track segment pulses from the same track therefore cause additional unit intensity light spots to illuminate the same approximate area. The track segment pulses associated with different

tracks, on the other hand, illuminate different areas whose horizontal positions along this same raster line are appropriate to the horizontal positions of these tracks in the raster.

When these areas of the photosurface on this particular raster line are scanned, a video output pulse is produced at each area whose amplitude is proportional to the sum of the unit intensity light spots projected onto the area. These video pulse amplitudes are a measure, therefore, of the number of track segment pulses appropriate to the in-focus lengths of the tracks in the field of view.

Finally, this particular line of the video output is selected from the 260 lines which compose the raster and subjected to an amplitude analysis which is designed to produce a single output pulse for each video pulse larger than some minimum amplitude.

The parameters of the system have been chosen so that tracks which are oriented within $\sim \pm 25^\circ$ relative to the vertical and whose in-focus length produces more than 6-7 track segment pulses will pass this amplitude criterion.

The result of the spot read-out system's analysis of the 5 tracks of Fig. III-4 is illustrated by the four large white spots at the bottom of this photograph. The fact that the two tracks at the extreme left overlap is responsible for the loss of one track count.

This type of loss is responsible for the saturation of the scanner at high track densities.

Automatic recording of data

Because of resolution limitations imposed by the television system, the area of the machine scanning swath is fixed at one-fourth the swath area employed by human observers. Hence, in order to compare human and machine results directly, the track pulse output from the spot read-out system is summed by a counter for four machine swaths before the track number is sent to the automatic recording section.

This number of tracks, N , in each group of four machine swaths is printed on paper tape and plotted, together with its standard error, $\pm\sqrt{N}$, as the y-coordinate by an x-y recorder. (The $\sqrt{N}$ is derived by a square root potentiometer mounted on the same shaft as the main balancing potentiometer.) The x-coordinate transitions of the recorder are locked to the swath transitions on the nuclear plate. The operation of this section yields, therefore, the reaction proton energy spectrum for the plate being machine scanned.

Because both weak and intense proton groups are often found on the same nuclear plate, two scales are employed in order to

examine both kinds of groups effectively: the normal 0-200 track scale and the 0-2000 track scale, which is automatically employed when $N > 200$.

Essential components

There are two components which, though smaller and less complex than the systems which have been discussed, are essential to the effective operation of the machine scanner. These are the pulsed light source and the automatic focus.

Pulsed light source.—The synchronous motor and the precision nut and screw arrangement (left side of Fig. III-1) are designed to move sixty distinct fields of view per second under the oil-immersion objective lens of the microscope. This arrangement matches the one-sixtieth of a second rate at which the Image Orthicon scans and wipes clean the projected image of the emulsion scene.

Because a steady illumination of the moving plate would smear the projected emulsion scene during this one-sixtieth of a second, a flash tube is arranged to illuminate the plate for a short time ($\sim 10 \mu\text{sec}$) in synchronism with the presentation of each new emulsion scene to the objective lens. This burst of light prints a stationary image on the photosurface of the Image Orthicon which then scans

the scene without interference from the nonilluminated motion of the nuclear plate under the microscope.

Automatic focus.—A modified oil-immersion lens is employed to maintain the in-focus slice of the emulsion at a constant depth beneath the emulsion surface. This is necessitated by tilts along the scanning swaths which are often caused by the seepage of immersion oil under the nuclear plates and by the presence of occasional distortions of the emulsion surface. These might allow the in-focus slice to rid out of the emulsion and thereby lose legitimate track counts and/or possibly produce spurious counts from track-like surface artifacts.

This automatic focusing of the microscope is arranged by spring loading the oil-immersion lens in order to keep a small ball (tungsten carbide) attached to the lens mount in contact with the immersion oil lubricated, tough surface of the emulsion. The lens is, therefore, constrained to follow the contour of the emulsion surface; the infocus slice of the emulsion remains at a constant emulsion depth.

Performance of the scanner

The machine scanner has proved to be a useful addition to the instrumentation associated with the cyclotron. Recent experience

has indicated that its speed is approximately that of a group of fifteen human observers. It is easy to scan all plates which can be produced by the cyclotron provided the limited performance specifications given below are acceptable. This means that adequately scanned data from surveys are available for analysis soon after the conclusion of the experiments.

At present a proton group must be about 10-15 tracks high in order to be detected reliably by the scanner; groups of weaker intensity are lost in the background composed of a few spurious machine tracks and real background tracks which might be rejected by human observers. This background is, usually, 3-5 tracks high. The fact that proton groups greater than 2000 tracks high saturate the machine does not constitute a machine limitation; this intensity is higher than is normally desirable except for extreme relative intensity comparisons.

An example of a plate scanned both by machine and by a human observer is given in Fig. III-5; this has been traced directly from the machine spectrum with portions of the horizontal axis removed in order to fit the comparison data in the limited region available. The human results are denoted by circles. (Note the scale shift from the 0-200 scale to the 0-2000 scale in plotting the tops of the three intense proton groups.) The consistent separation in

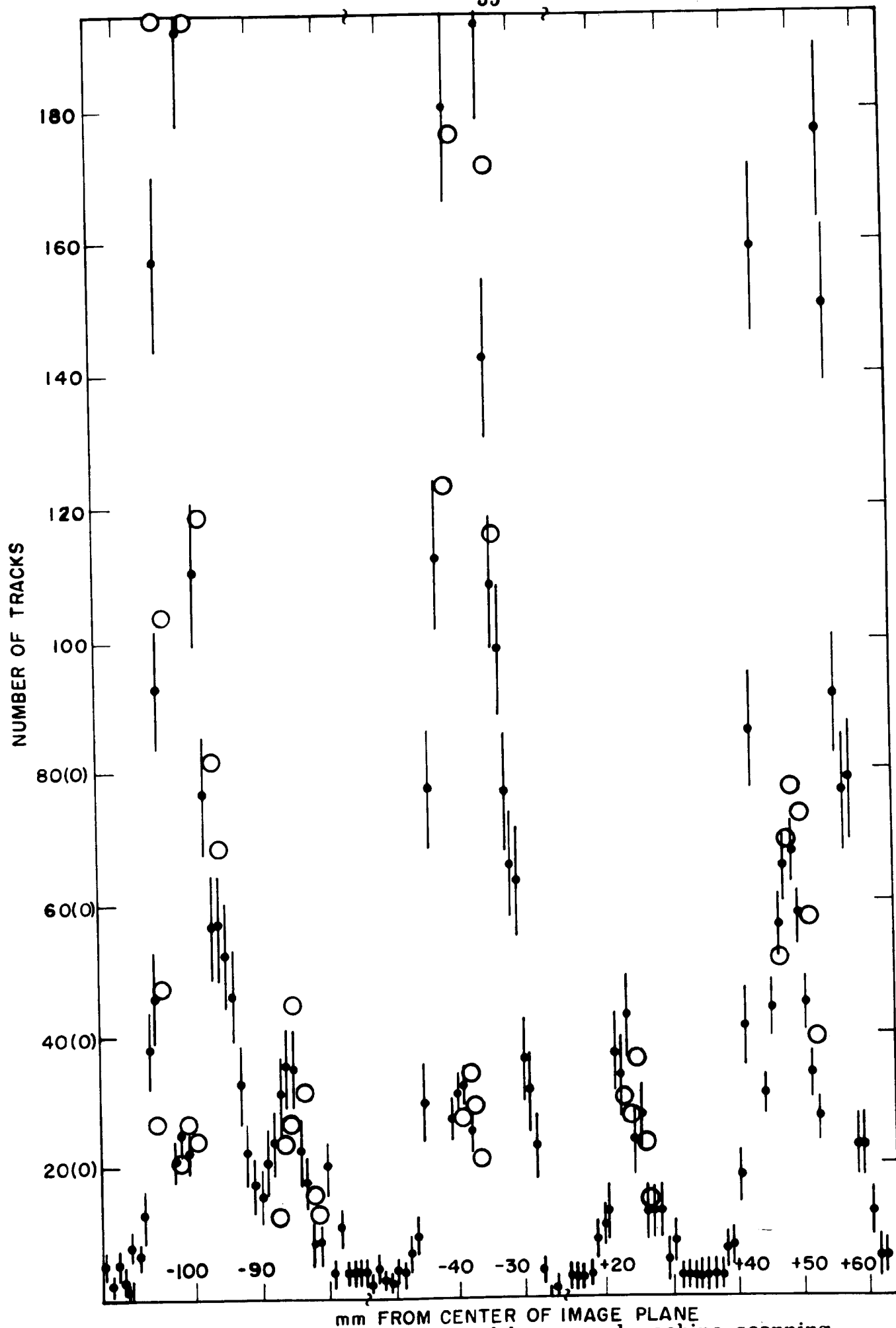


Figure III-5.—Comparison of human and machine scanning.

abscissa of the peak maxima between the two scans is caused by the small, relative misalignment of the nuclear plate between the two scanning microscopes used. The good correspondence between the two intensities portrayed for each proton group and the low background between groups is an indication of good machine performance for this particular plate.

A study of a large number of proton group intensities has indicated that for equal geometrical areas the scanner efficiency (defined as the ratio of the machine measurement of the intensity of a proton group to the human measurement of the same group) falls between 80 percent and 120 percent. This large variation in scanner efficiency has necessitated human scanning of the peak regions (such as in Fig. III-5) in order to establish absolute intensities for angular distribution and relative intensity studies.

It has been found that the variable scanner efficiency is intimately related to the fact that although the geometrical areas are arranged to be the same for both human and machine scanning, the search areas are not necessarily the same. The search area is defined as the geometrical area plus that added area which contains acceptable tracks that protrude sufficiently far into the geometrical area to be counted by the machine scanner. If it were possible to establish a nonvariable search area for the scanner, a constant

efficiency would result since the search area for a human is presumed to be constant. Because the search area depends sensitively on the criteria established for track acceptability and parameters of the optical and television systems, however, a different approach is being considered.

Here a slow-speed scan through peaks is arranged such that at least one-third of each field of view is presented in three successive emulsion scenes. The system will be designed to count each track only once even though each track will probably be recognized as such at least twice. Because of its insensitive dependence on the track acceptability criteria and scanner parameters, this method shows promise of establishing the machine scanner as an absolute counting device.

CHAPTER IV

EXPERIMENTAL RESULTS

Surveys

Two surveys were performed over an energy region which extended from ~ 1.5 -Mev below the known position of the O^{19} ground state ($Q = 1.730$ -Mev) to an excitation energy of ~ 4.5 -Mev.

Both surveys were run at reaction angles of 15° and 45° . The 15° angle was chosen because, as an examination of the Butler curves for this energy region shows, this angle yields a reasonable compromise between the intensities expected from possible s, p, and d neutron captures. The 45° angle was chosen in order to identify unknown O^{19} proton groups on the basis of their observed energy shift with reaction angle. In view of the presence of contaminant nuclei of approximately the same mass, and therefore possessing approximately the same energy-angle shift as O^{19} , corresponding sets of data were required at angles separated by at least 30° . This separation yields an energy shift for a mass 19 nucleus that differs by at least 0.015-Mev from the mass 18 or mass 20 shift.

The first survey employed an O^{18} -enriched target only so that the energy-angle shift was the sole means of unknown peak identification. The second survey employed an enriched target and a non-enriched target which were alternately used at each position. In this survey O^{19} identification was made primarily on the basis of a peak's appearance in the enriched sequence but not in the nonenriched sequence; the energy-angle shift served as a check

Kodak NTB nuclear track plates were used to detect the (d,p) reaction protons and were, for the most part, scanned by the machine scanner. Due to poor development, several plates were too opaque to be machine scanned and were, therefore, scanned by human observers. Also, in certain restricted regions of high background, human scanning was employed to check the machine data.

Two new levels of O^{19} at 3.14-Mev and 3.94-Mev excitation were identified as a result of these surveys. In addition, no O^{19} level was found in the region below the ground state between $Q = 1.730$ -Mev and $Q \approx 3.2$ -Mev. This absence indicates that the $Q = 1.730$ -Mev level is the O^{19} ground state and confirms the similar result of Ahnlund (22) at $E_d = 4.98$ -Mev.

There were two limitations inherent in these surveys.

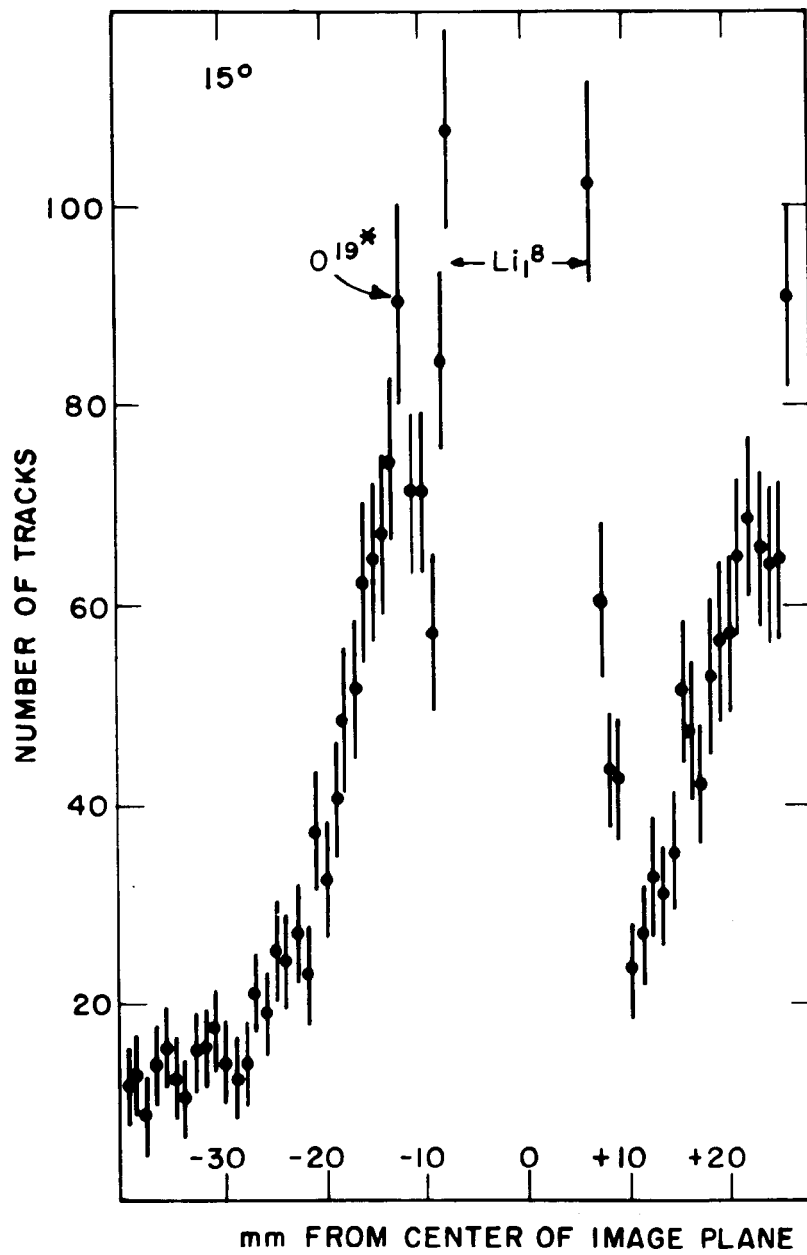
First, due to the necessity of reasonable bombardment durations, O^{19} levels possessing an intensity <15 percent of the ground state

intensity at 15° could not have been reliably detected. Second, because of the nature of the contaminants present in the target (Li^7 , O^{16} , C^{12} , and H^1), there are regions (see Appendix C, Fig. C-1) where O^{19} levels of greater than minimum intensity could have been submerged in the strong proton groups associated with (d,p) reactions on these contaminant nuclei. This is particularly true at 15° in the regions of the C_2^{13} and O_2^{17} proton groups and the C_3^{13} , Li_1^8 , and the knock-on proton groups corresponding to O^{19} excitation energy regions from 2.2–2.3-Mev and 2.7–3.1-Mev, respectively.

The spectrum of Fig. IV-1 illustrates a portion of this region. The proton group associated with the 3.14-Mev level of O^{19} rests on the low energy tail of the Li_1^8 group which in turn rests on the low energy tails of the O_2^{17} , C_2^{13} and proton knock-on groups (not shown) whose combined peak intensity is greater than five times that of the Li_1^8 peak intensity.

The Q-values for the (d,p) reactions leading to these new levels were determined by a modification of the comparison technique described in (15). In this modified method the Q-value of a known proton group near the O^{19} group is used to calculate the deuteron beam energy appropriate to this restricted neighborhood; the calculation is then inverted so as to determine the unknown O^{19} Q-value from this calculated beam energy.

FIG. IV-1. $O^{18}(d,p)O^{19}_{(3,14)}$
PROTON SPECTRUM



The comparison Q-value employed for the 3.14-Mev level calculation was $Q = -1.166 \pm 0.015$ -Mev for the neighboring Li_1^8 group and was taken from (23, 24). This led to a Q-value for the 3.14-Mev level in O_{19} of $Q = -1.41 \pm 0.02$ -Mev.

The comparison Q-value employed for the 3.94-Mev level calculation was $Q = -1.928 \pm 0.007$ -Mev for the neighboring O_3^{17} group and was also taken from (23, 24). This led to a Q-value for the 3.94-Mev level in O^{19} of $Q = -2.21 \pm 0.02$ -Mev.

(d,p) Angular distributions at $E_d \cong 7.8$ -Mev

The angular distribution measurements were complicated by the loss of O^{18} from the target under deuteron bombardment. A similar effect had been noted by Zimmerman (13) although, in view of the differences between the targets employed in his investigation and the enriched LiOH targets used in this experiment, the mechanisms responsible for the O^{18} loss may not have been the same. This progressive loss necessitated systematic correction of measured group intensities in the angular distributions concerned with the weak 3.14-Mev and 3.94-Mev levels where the bombardments were necessarily long.

The percentage loss in O^{18} as a function of the total number of deuterons incident upon the target (a measure of this number was

given by a double proportional counter telescope used to monitor the number of reaction particles in a small solid angle) was found to follow a simple exponential curve with a decay constant of 1-1/2 percent per 1000 monitor counts (a typical exposure being 5000 monitor counts). The systematic correction applied was, therefore, the inverse of this observed exponential decay.

The correction was applied first, in a given angular distribution, to the normalizing plates placed at regular intervals throughout the run. In all cases where the correction curve was employed, matching the initial and final normalizing peak intensities from the curve would also yield the proper corrections for the remaining normalizing peak intensities within the usual statistical uncertainties associated with these intensities. This feature led to confidence in the correction, even though the detailed mechanism responsible for the O^{18} loss was not clear.

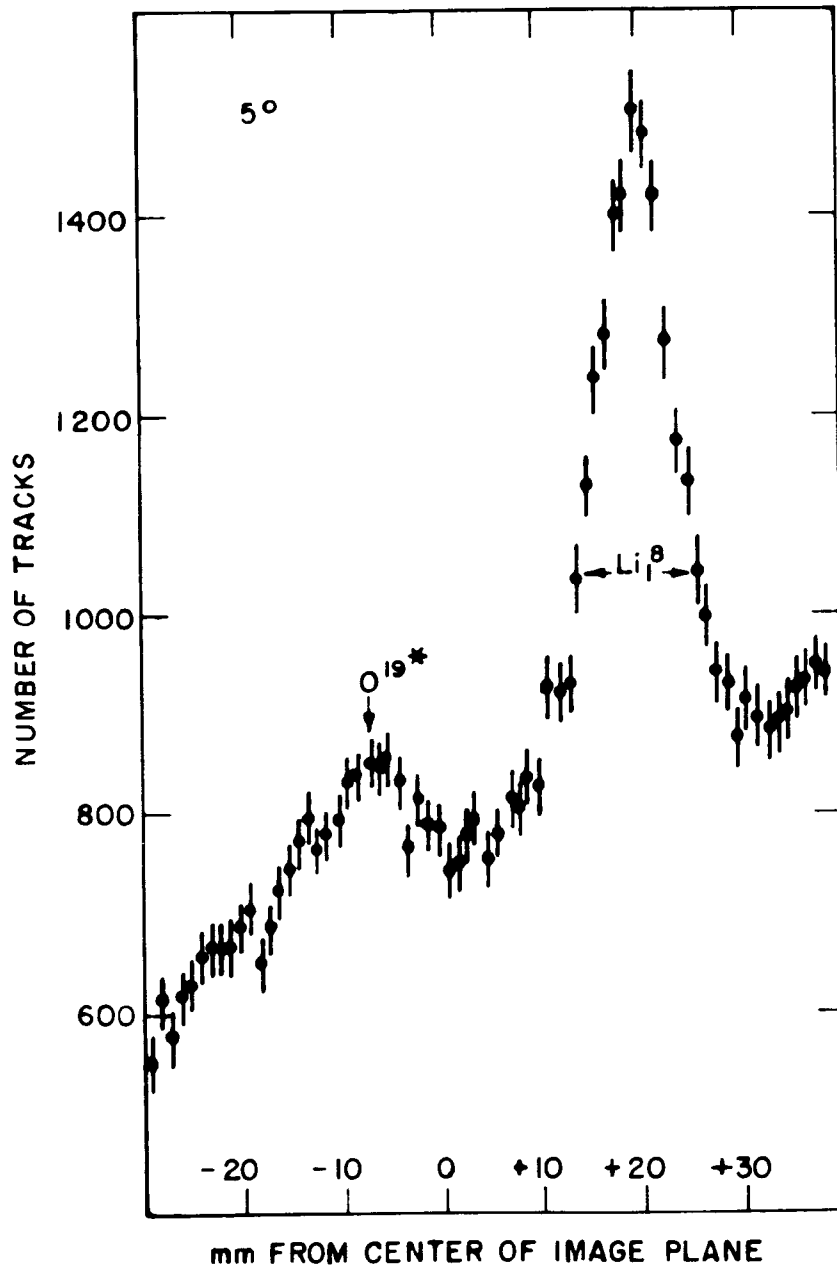
Due to the presence of background tracks, an additional correction was also applied to all the measured peak intensities. The mean background level over the region covered by a given O^{19} proton group was estimated from the scanning results on either side of the group. In cases where the O^{19} group was sitting on the low energy tail of a more intense group, the mean trend of the tail was estimated. In addition, the uncertainty associated with this mean background was estimated by requiring the presence

of at least 75 percent of the measured background fluctuations within the estimation. The correction, which normally was small, consisted of subtracting the estimated background from the measured intensity of the group and combining the uncertainty in the background with the normal statistical uncertainty of the group intensity under the assumption that the uncertainties were statistically independent.

In the few cases of large backgrounds at the forward reaction angles this led to large errors. A limited portion of the spectrum of the 5° point in the angular distribution of the 3.14-Mev level is shown in Fig. IV-2 as an example. Here the O^{19} peak has a height of about 80 tracks at maximum and is nearly submerged in a background that averages 680 tracks across the peak region. This background is due to the extensive tail of the C_3^{13} peak (not shown) and was described in Chapter II. (It should be pointed out that prior to the introduction of the five tungsten apertures, the machine scanner saturated at every point in the spectrum indicating a count uniformly in excess of 2000). Consequently, a large uncertainty exists in the intensity of the O^{19} group; this is shown in the angular distribution of Fig. IV-5.

The Lubitz Tables (25) were used to calculate the theoretical Butler-Born angular distribution curves for all cases and considerably simplified the cut-and-try method of fitting appropriate curves

FIG. IV-2. $O^{18}(d,p)O^{19}_{(3,14)}$
PROTON SPECTRUM



to the angular distributions associated with the 3.14-Mev and 3.94-Mev levels.

Ground state angular distribution.—This angular distribution, shown in Fig. IV-3, is clearly fitted by an $l_n = 2$ curve with a value of 5.1f ($f = 10^{-13}$ cm) for the Butler radius.

The $l_n = 2$ capture value agrees with the analysis by Popic (26) of data taken by Ahnlund (27) at $E_d = 0.8$ -Mev and with Zimmerman's results (13) at $E_d = 2.50$ -Mev.

Since the character of the O^{18} ground state is $J^\pi = 0^+$ (14), the $l_n = 2$ value clearly indicates $J^\pi = 3/2^+$ or $5/2^+$ for the ground state of O^{19} .

First excited-state angular distribution.—Several angular distribution studies of this state did not lead to consistent results and, hence, no attempt at their interpretation has been made.

Data taken by Ahnlund (27) at $E_d = 0.8$ -Mev and analyzed by Popic (26) suggest $l_n = 1$ and therefore odd parity for this state. Zimmerman (13), on the other hand, observed almost complete isotropy at $E_d = 2.50$ -Mev.

Second excited-state angular distribution.—The angular distribution for this state is shown in Fig. IV-4. A Butler radius of

FIG. IV-3. GROUND STATE
ANGULAR DISTRIBUTION

$$O^{18}(d,p)O_0^{19}$$
$$r_0 = 5.1 \times 10^{-13} \text{ cm}$$

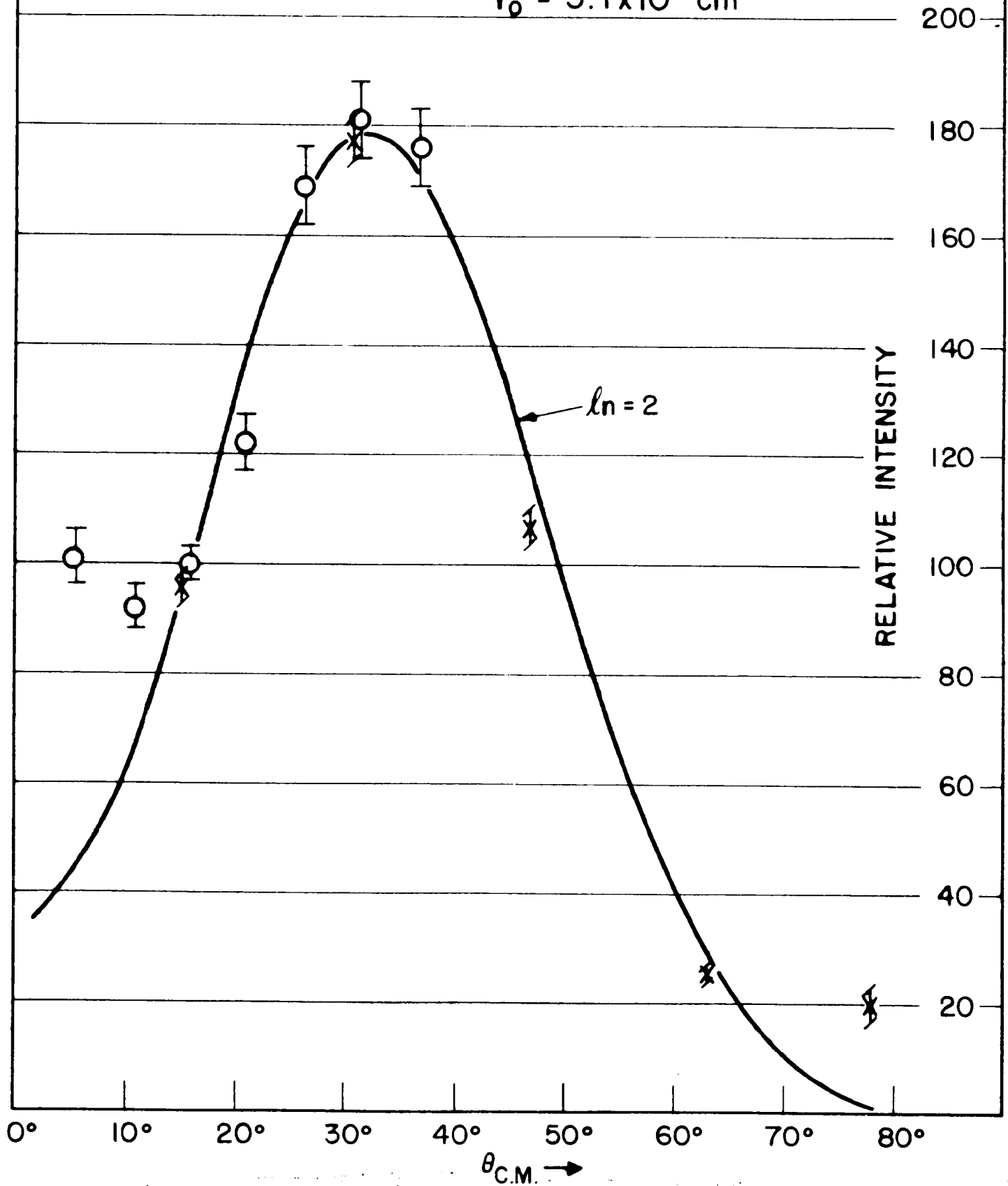
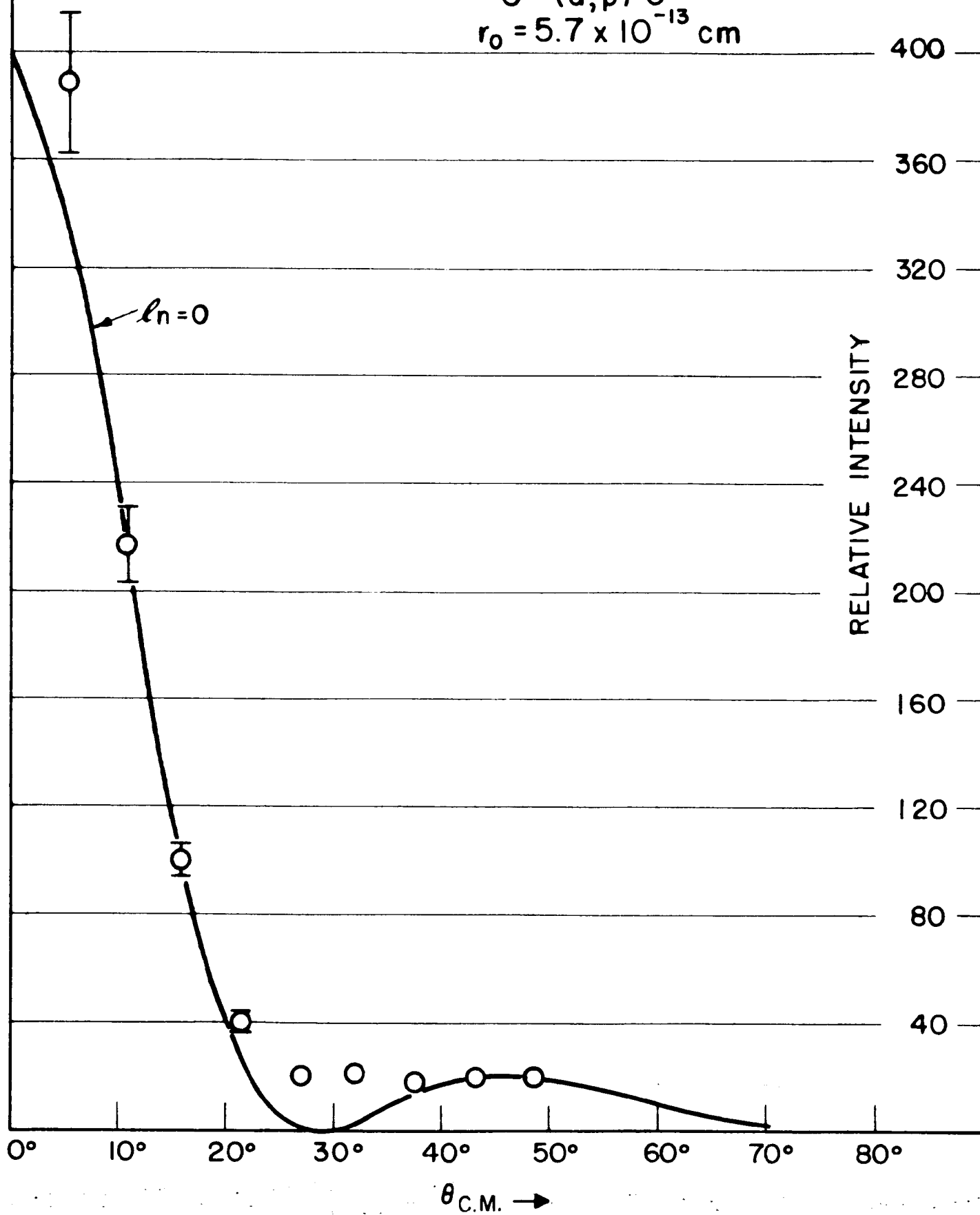


FIG. IV-4. SECOND EXCITED STATE
ANGULAR DISTRIBUTION

$$O^{18}(d,p)O^{19*}$$
$$r_0 = 5.7 \times 10^{-13} \text{ cm}$$



5.7 f has been employed to fit the $l_n = 0$ curve required by the data. A somewhat better fit at 5° is effected by changing the radius to 6.0f, but this is accomplished at the expense of the 10° and 20° points and involves, basically, a matter of taste.

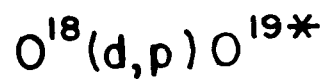
The assignment of $J^\pi = 1/2^+$ to this state follows directly from the $J^\pi = 0^+$ character of the O^{18} ground state. This assignment confirms the results of Stratton (12) at $E_d \cong 2\text{-Mev}$ and Zimmerman (13) at $E_d = 1.74\text{-Mev}$.

3.14-Mev-state angular distribution.—Two Butler curves are used to fit the angular distribution shown in Fig. IV-5: an $l_n = 0$ curve with a radius of 4.5f and an $l_n = 1$ curve with a radius of 8.0f.

The striking similarity of these two curves illustrates the difficulty in assigning unambiguous l_n values in regions of low and negative Q-values.

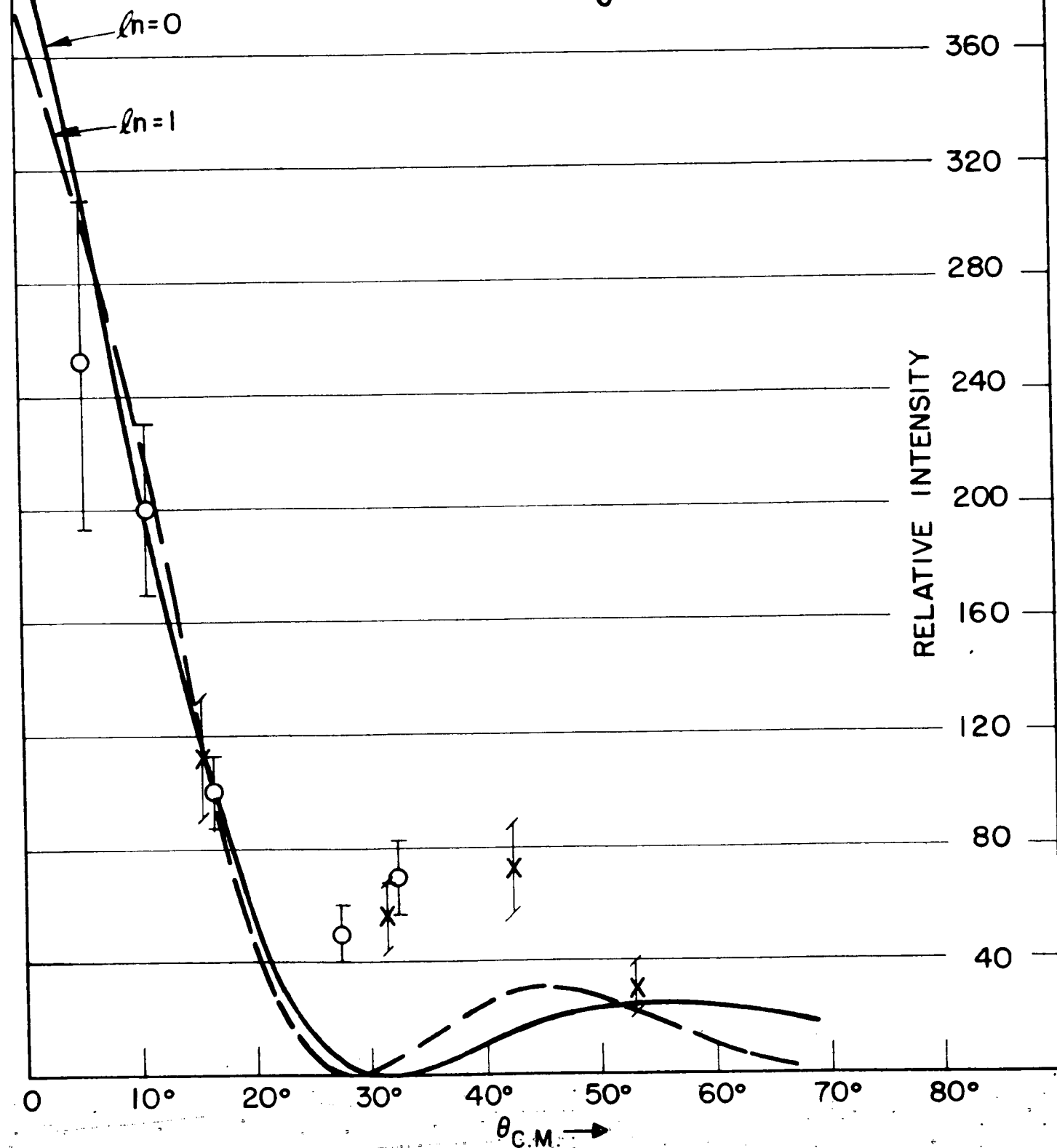
The large uncertainty in the relative intensity at the 5° point was caused by a severe background problem (shown in Fig. IV-2). Because this relative intensity value is of great importance to the selection of the appropriate l_n value, the raw 5° data were scanned once by machine and twice by human observers—each one of whom employed a different scanning procedure. On the basis of these

FIG. IV-5. 3.14-Mev STATE
ANGULAR DISTRIBUTION



$$\ell n=0 - r_0 = 4.5 \times 10^{-13} \text{ cm}$$

$$\ell n=1 - r_0 = 8.0 \times 10^{-13} \text{ cm}$$



three spectra it is felt that the stated relative intensity of 250 ± 60 represents the minimum value for this point.

The effect of this assessment on the two radii was tested by forcing the two curves (not shown) through the minimum relative intensity value at 5° consistent with the calculated uncertainty at this point and by requiring, at the same time, a reasonable fit at the other angular positions. This resulted in a radius of $\sim 4.3f$ for the $l_n = 0$ curve and a radius of $\sim 7.5f$ for the $l_n = 1$ curve; both curves passed through 5° at relative intensity values near 220.

The curves shown in Fig. IV-5 were drawn, on the other hand, to represent a compromise between the minimum value chosen for the 5° point and a less pessimistic assessment of the 5° data.

Because the radius associated with the $l_n = 0$ curve (4.3–4.5f) is more consistent with the ground and second excited state radii of 5.1f and 5.7f than is the radius associated with an $l_n = 1$ curve (7.5–8.0f), the $l_n = 0$ curve has been chosen as the appropriate curve for the 3.14-Mev state.

This leads directly to the assignment of $J^\pi = O^+$ for the 3.14-Mev state.

3.94-Mev-state angular distribution.—Again two theoretical curves have been chosen to fit the observed angular distribution

shown in Fig. IV-6: an $l_n = 1$ curve with a radius of 4.9f and an $l_n = 2$ curve with a radius of 8.0f.

A drop of 0.5f in the radius of the $l_n = 2$ curve to 7.5f produces a better fit at the forward angles, but this is accomplished at the expense of the 20° and 25° points; 7.5f should, therefore, be regarded as the minimum radius that could be employed for $l_n = 2$.

The $l_n = 1$ value has been selected as the appropriate curve for the 3.94-Mev state because the radius of 4.9f is consistent with the radii employed in the previous three angular distributions.

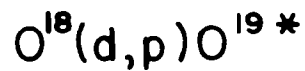
The character of the state is, therefore, $J^\pi = 1/2^-$ or $3/2^-$.

Relative intensities

Measurements were made to determine the intensities of the four known excited states relative to the ground state intensity.

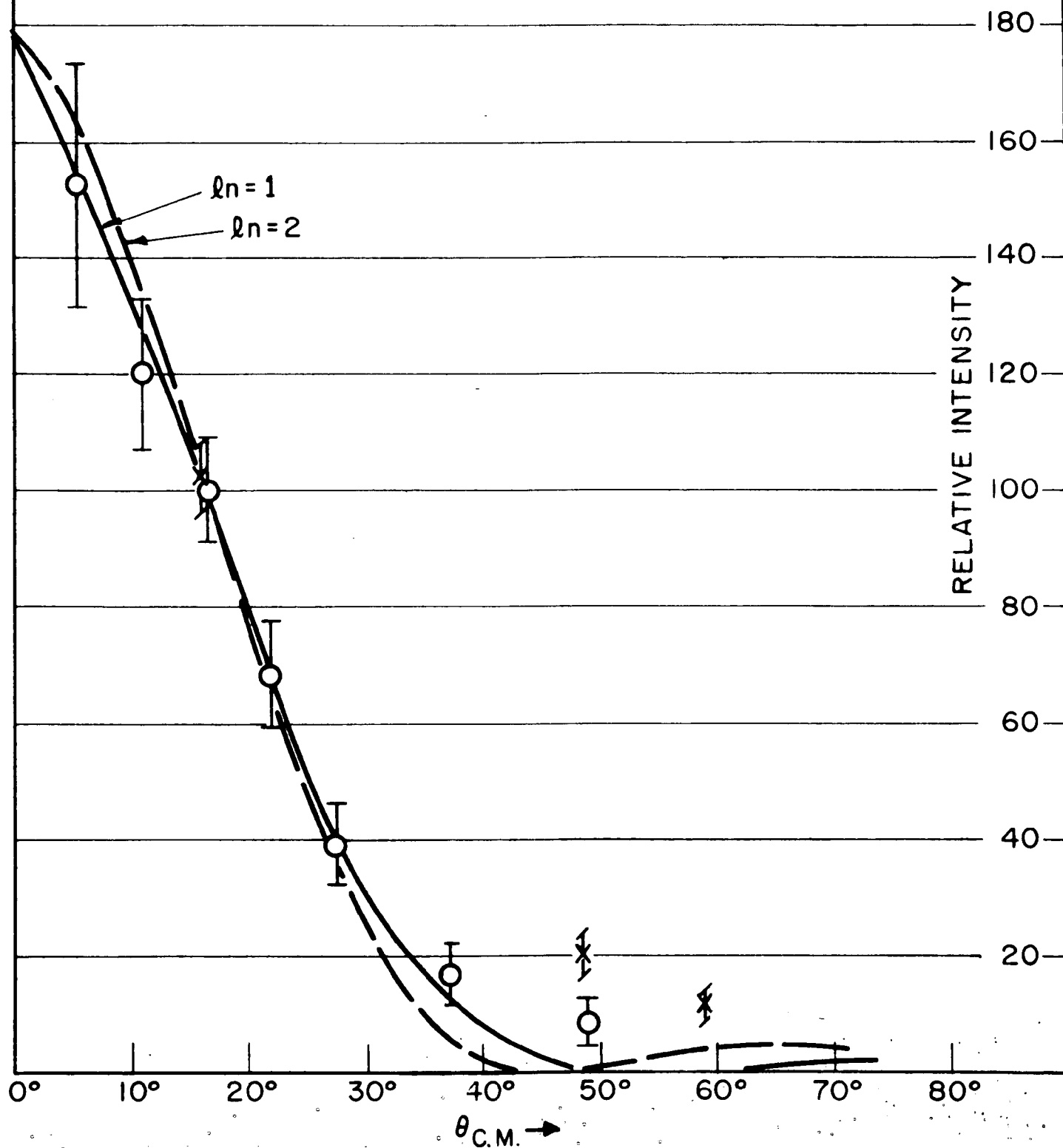
In order to make meaningful intensity comparisons, the conditions under which the intensity of an excited state is measured must be—in so far as possible—identical to the conditions imposed upon the ground state measurement. Thus, the bombardment duration, the target employed and the various machine parameters (slit settings, use of velocity filter, etc.) are held constant over the excited state intensity run and the ground state run against which it is to be compared.

FIG. IV-6. 3.94 Mev STATE
ANGULAR DISTRIBUTION



$$\ell n=1 - r_0 = 4.9 \times 10^{-13} \text{ cm}$$

$$\ell n=2 - r_0 = 8.0 \times 10^{-13} \text{ cm}$$



The determination of the relative intensity of the weak first excited state was particularly simple because of its proximity (0.096-Mev) to the ground state; both proton groups were recorded simultaneously on the same nuclear plate.

These results are summarized in Table IV-1. The reaction angles (in the lab system) at which the intensity comparisons were made and the l_n -values and Butler radii, determined from the angular distribution studies, are also listed for completeness.

TABLE IV-1
EXPERIMENTAL RELATIVE INTENSITIES

State	E (Mev)	Angle	l_n	Radius (f)	Relative Intensity
Ground . .	0	—	2	5.1	1
First	0.096	30°	—	—	0.027±0.003
Second . .	1.470	15°	0	5.7	4.82±0.25
3.14-Mev .	3.14	15°	0	4.5	0.35±0.05
3.94-Mev .	3.94	15°	1	4.9	0.48±0.05

CHAPTER V

CONCLUSION

The calculations of Elliott and Flowers (5) and Redlich (6, 7) have served as the theoretical guides for much of this investigation of the level structure of O^{19} . Both calculations were designed to deal only with the low-lying even parity states of mass 18 and mass 19 nuclei and thus were based on the assumption of an unexcited, doubly-magic O^{16} core.

Elliott and Flowers chose a Yukawa well shape and a Rosenfeld exchange mixture to describe the interparticle interaction. The range of this interaction was fixed at 1.4f which would require a well depth, V_c , of 50-Mev to yield the correct deuteron binding energy. The strength, $\mathfrak{V}$, of the nuclear spin-orbit interaction, $\mathfrak{V} \sum_i \vec{s}_i \cdot \vec{l}_i$, was fixed at 2-Mev; this followed from the observed 5-Mev splitting between the $d_{5/2}$ and $d_{3/2}$ states in O^{17} . The calculation was carried out in the intermediate coupling scheme in which the ratio $\mathfrak{V}/V_c$ plays the role of the intermediate coupling parameter; V_c is regarded as the free parameter.

Redlich, on the other hand, selected a Gaussian well with a Serber exchange mixture to describe the interparticle interaction. In this case the parameters were chosen such that the well depth of ~70-Mev would give the correct properties of the deuteron (excluding the quadrupole moment). The separation of the s-d levels produced by the nonoscillator character of the core potential and the nuclear spin-orbit interaction were inserted into the calculation by means of a single-particle energy operator constructed to give the correct excitation energy of the $d_{5/2}$, $s_{1/2}$, or $d_{3/2}$ state in O^{17} upon substitution of the appropriate angular momentum value. The extent of the intermediate coupling is determined (as in the work of Elliott and Flowers) by the relative strength of this single-particle energy operator and the depth of the interparticle potential. (Redlich considered 70.8-Mev and 1.46 times this depth.)

Both calculations consider the levels of mass 18 and mass 19 nuclei in configuration interaction. This is based upon the fact that in both O^{17} and F^{17} the $d_{5/2}$ and $s_{1/2}$ levels are close to one another (0.871-Mev and 0.500-Mev, respectively), and the assertion that for any reasonable nuclear field these $d_{5/2}$ and $s_{1/2}$ levels will remain close to one another. (If the nuclear field were, for example, a harmonic oscillator field, the 1d and 2s levels would coincide.) Because the two calculations are concerned with the

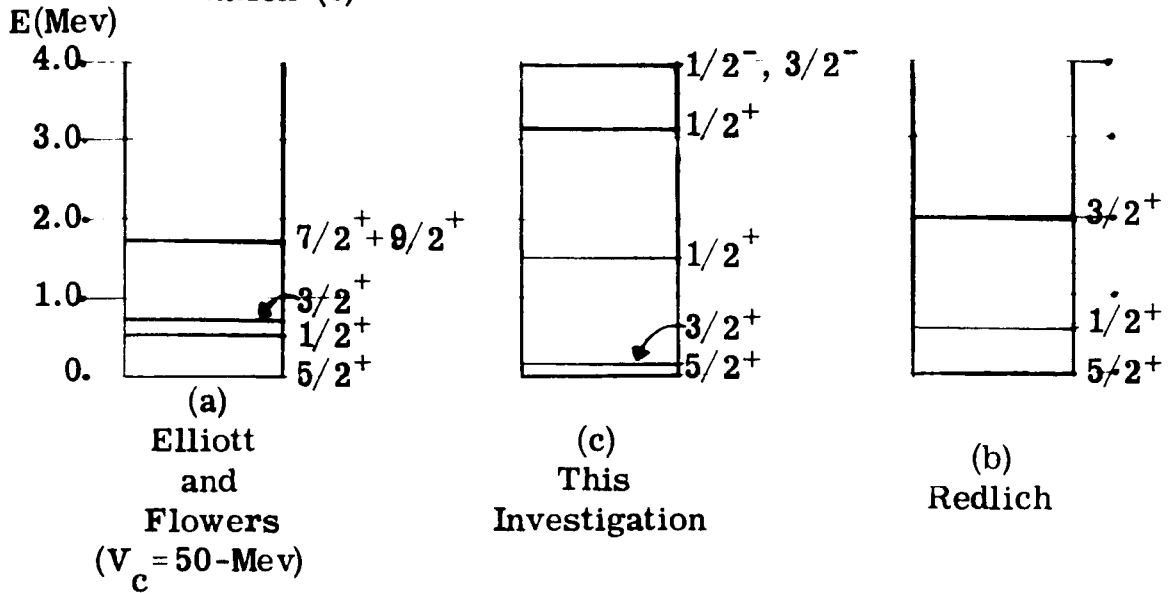
low-lying level structure, the configuration mixtures are predominantly Type 0 configurations.

The Type 0 configurations are three particle configurations constructed from $d_{5/2}$ and $s_{1/2}$ components only, and lead to states which should lie below 5-Mev excitation. Of course, Type 1 configurations (one $d_{3/2}$ component which lies at ~5-Mev in O^{17} and F^{17}) and Type 2 configurations (two $d_{3/2}$ components) can be, and are, present in the form of small admixtures to the basic Type 0 configurations. Redlich incorporated both Type 1 and Type 2 configuration admixtures into his calculations; Elliot and Flowers, on the other hand, consider only Type 1 admixtures.

If even parity states in a region ~5-Mev above the Type 0 region were being investigated, the Type 1 configurations would predominate with Type 0 and Type 2 configurations providing the admixtures. Whereas a consideration of the high-lying even parity states at 10-15-Mev above the Type 0 region would involve mainly Type 2 configurations, the Type 0 and Type 1 configurations being admixed.

The level structure predictions of these two calculations are presented in Fig. V-1 together with the results of this investigation. (These predictions have already been illustrated in Fig. I-1 and are repeated for convenience.) In addition, their percentage analyses of

Fig. V-1. The level structure of O^{19} predicted by (a) Elliott and Flowers, and (b) Redlich, and observed in this investigation (c).



the state wave functions into jj -coupled configurations for both the ground state of O^{18} [the initial state for the (d,p) stripping reactions employed throughout this investigation] and the predicted $5/2^+$, $1/2^+$, and $3/2^+$ states of O^{19} are given in sections (a) and (b), respectively, of Table V-1. (The d and s designations have been dropped for reasons of simplicity.)

Relative reduced widths

These percentage analyses of the O^{19} wave functions into jj -coupled configurations for the $5/2^+$, $1/2^+$, and $3/2^+$ states have been employed to calculate the theoretical reduced widths of the $3/2^+$ state and the $1/2^+$ state relative to the $5/2^+$ state.

TABLE V-1

PERCENTAGE ANALYSES OF WAVE FUNCTIONS
INTO jj-COUPLED CONFIGURATIONS

(a) O^+ Ground State of $O^{18}(T=1)$

$(5/2)^2$ (pct.)	$(1/2)^2$ (pct.)	$(3/2)^2$ (pct.)	Total Type O (pct.)	Reference
79	15	6	94	Elliott and Flowers (5)
74	16	10	90	Redlich (6, 7)

TABLE V-1 (Continued)

(b) States of Low Excitation in $O^{19}(T=3/2)^a$

J	jj						Total Type O (pct.)	Reference
	$(5/2)^3$ (pct.)	$(5/2)^2$ (3/2) (pct.)	$(3/2)^2$ (5/2) (pct.)	$(5/2)^2$ (1/2) (pct.)	$(3/2)^2$ (1/2) (pct.)	$(1/2)^2$ (5/2) (pct.)		
$5/2^+$	82	7	X		X	11	93	Elliott and Flowers (5)
	72	1	9			18	90	Redlich (6, 7)
$1/2^+$	—		X	92	8	X	92	Elliott and Flowers (5)
	—			90		9	90	Redlich (6, 7)
$3/2^+$	62	3	X	33	2	X	95	Elliott and Flowers (5)
	53		2	42	2		95	Redlich (6, 7)

^aA dash indicates the nonparticipation of a configuration in the formation of a state. A blank indicates a negligible percentage contribution. Type 2 configurations not considered by Elliott and Flower are indicated by a cross.

The reduced width of a state formed by (d,p) stripping is a measure of the overlap of the final state wave function of definite spin, J_f , with the wave function of the initial state (ground state of the target nucleus) of definite J_i coupled to the stripped neutron of definite j_n to form a state characterized by J_f . Thus, only that fraction of a configuration of the final state wave function which has as its parent a configuration found in the wave function of the ground state of the target nucleus can be stripped to.

Consider, for example, the $(5/2)^3$ configuration in the $5/2^+$ state of O^{19} . The only part of this jj-coupled configuration that can be constructed by adding a $j_n = 5/2$ neutron to the O^{18} ground state wave function is the fraction of $(5/2)^3$ made up of two particles coupled to zero (the parent configuration found in the O^{18} ground state wave function) and then coupled to the $j_n = 5/2$ neutron to form the final $5/2^+$ state. This is written as $(5/2)_0^2 \times 5/2$ to distinguish it from the other possible parent configurations $(5/2)_2^2$ and $(5/2)_4^2$ which can lead to a final $5/2^+$ state.

The fractional parentage coefficients appropriate to the O^{18} (d,p) O^{19} results have been taken from French and Raz (28). Since these coefficients enter into the reduced width calculations in squared form, Table V-2 lists the squares of the fractional parentage coefficients used in these calculations.

TABLE V-2

SQUARES OF FRACTIONAL PARENTAGE COEFFICIENTS FOR
 O^{19} STATES HAVING THE O^{18} GROUND STATE
 CONFIGURATIONS AS PARENTS^a

J	jj						
	$(5/2)_0^2$	$(3/2)_0^2$	$(3/2)_0^2$	$(5/2)_0^2$	$(3/2)_0^2$	$(1/2)_0^2$	$(1/2)_0^2$
	$\times 5/2$	$\times 3/2$	$\times 5/2$	$\times 1/2$	$\times 1/2$	$\times 5/2$	$\times 3/2$
$5/2^+$	2/9	0	1/3	0	0	1/3	—
$1/2^+$	—	0	0	1/3	1/3	—	—
$3/2^+$	0	1/3	0	0	0	—	1/3

^aA dash indicates the nonparticipation of a configuration in the formation of a state.

The theoretical relative reduced widths have been calculated from formula (2) of French and Raz (28) as corrected by Bilaniak and Hough (17) and from the numbers given in Table V-1 and Table V-2. This formula can be written as:

$$\theta_{J_f}^2 = \sum (A_{18}^2)_0 f_{0J_f}^2 (A_{19}^2)_{J_f} \quad (V-1)$$

where:

$\theta_{J_f}^2$ = the reduced width of an O^{19} state of spin J_f in units of the single-particle reduced width

$(A_{18}^2)_0$ = the percentage weight (square of the amplitude) of the jj-coupled configuration of the $O^{18} J = 0$ state (ground state) wave function (Table V-1a)

$(A_{19}^2)_{J_f}$ = the percentage weight (square of the amplitude) of the jj-coupled configuration of the $O^{19} J = J_f$ state wave function (Table V-1b)

$f_{0J_f}^2$ = the square of the fractional parentage coefficient for the $O^{19} J = J_f$ state configuration having the $O^{18} J = 0$ state configuration as a parent (Table V-2)

and where the sum is to be taken over all the jj-coupled configurations of the $O^{19} J = J_f$ state. As an example of the use of this formula, the reduced width of the $5/2^+$ state of O^{19} employing the Redlich wave functions is seen to be:

$$\theta_{5/2}^2 = (0.74)(2/9)(0.72) + (0.74)(0)(0.01) + (0.10)(1/3)(0.09) + (0.16)(1/3)(0.18) = 0.131.$$

The experimental relative reduced widths were calculated using formula (10) of Lubitz (25) and the observed relative intensities given in Table IV-1. The Lubitz formula can be written as:

$$\frac{d\sigma_{dp}}{d\Omega} = \frac{2J_f + 1}{2J_0 + 1} \theta_{J_f}^2 \mathcal{P}_1^{(2)} \quad (V-2a)$$

or, expressing $\mathcal{P}_1^{(2)}$ explicitly

$$\frac{d\sigma_{dp}}{d\Omega} = \frac{2J_f + 1}{2J_0 + 1} \theta_{J_f}^2 \left[86.3 \left(\frac{m+1}{m+2} \right)^2 \text{tr}_0^3 \sigma_{TAB}^1 \right] \quad (V-2b)$$

where:

$\frac{d\sigma_{dp}}{d\Omega}$ = the stripping cross section in mb/ster

J_f = the spin of the final state

J_i = the spin of the initial state

$\theta_{J_f}^2$ = the reduced width of the final state in units of the single-particle reduced width

$\mathcal{P}_1$ = the intrinsic Butler single-particle cross section

m = the mass of the initial nucleus in amu

$t = \left[\frac{m+2}{2(m+1)} \left(\frac{m}{m+2} + \frac{Q}{E_d} \right) \right]^{1/2}$ in which E_d is the deuteron energy and Q is the Q -value for the state in question

r_0 = the Butler radius used to fit the experimental angular distribution with the theoretical Butler curve for a neutron capture value of $l_n = 1$.

σ_{TAB}^1 = the angular dependence of the Butler cross section; this is given in the Lubitz tables.

It should be pointed out that the experimental reduced width of the 0.096-Mev state relative to the ground state was calculated on the assumption that the state is the $3/2^+$ state predicted by theory and thus would exhibit an $l_n = 2$ capture angular distribution similar in shape and radius to the angular distribution of the ground state.

In the experimental relative reduced width calculations for the second excited state, the 3.14-Mev state and the 3.94-Mev state two different l_n -value angular distributions are being compared. But, because of the insecure basis of the Butler theory, relative intensity comparisons for different l_n -values are less certain than those for the same l_n . This means that only those states reached by neutron capture with the same l_n should be compared directly. The accuracy of these experimental relative reduced widths is, therefore, limited mainly by the Butler theory itself.

The results of these calculations are summarized in Table V-3.

Spins and parities of the O^{19} states

The experimental evidence which has been utilized up to this point in the initial identification of the level structure of O^{19} has resulted mainly from the (d,p) angular distribution studies of this investigation and others. Additional experimental evidence applicable to the O^{19} level structure problem is provided by the relative reduced widths of this investigation, the well-known β^- decay to F^{19} and the measured lifetime of the first excited state.

Ground state.—The ground state of O^{19} is identified as the $5/2^+$ state predicted by the Elliott and Flowers and the Redlich

TABLE V-3
REDUCED WIDTHS OF O^{19} STATES RELATIVE
TO $5/2^+$ GROUND STATE

State	J	Experi- mental	Theoretical	
0.096-Mev	$3/2^+$	0.040	0.055	Elliott and Flowers
			0.003	Redlich
1.470-Mev	$1/2^+$	3.83	1.68	Elliott and Flowers
			1.72	Redlich
3.14-Mev	$1/2^+$	0.43	—	
3.94-Mev	$1/2^-$	0.20		
	$3/2^-$	0.10		

calculations. This identification follows, basically, from two pieces of evidence.

First, the $5/2^+$ state is predicted by both theories to be an intense stripping state in comparison to the $3/2^+$ state which can be formed by stripping only through a small Type 1 configuration admixture in the predominantly Type 0 wave function. In comparison to the almost single-particle $1/2^+$ state, the $5/2^+$ state is predicted

to be moderately strong. Since the observed $1/2^+$ second excited state at 1.470-Mev is clearly the $1/2^+$ state predicted by theory, the ground state must be denoted as the $5/2^+$ state predicted by theory on the basis of its observed, moderately strong intensity relative to the second excited state.

Second, the absence of an observed β -decay to the ground state of F^{19} supports this designation of $5/2^+$ for the O^{19} ground state. O^{19} is observed to decay to the $3/2^+$ level at 1.57-Mev excitation and also to the $5/2^+$ level at 0.198-Mev excitation. If the O^{19} ground state were $3/2^+$, a decay to the $1/2^+$ ground state of F^{19} would be observed.

Mayer (1) and Redlich (6) have mentioned the possibility of a $3/2^+$ ground state and cite the $3/2^+$ ground state spin and parity of Na^{23} (having three protons outside the core, the four extra-core neutrons coupled, in pairs, to zero) as an example of a nucleus in which the individual nucleons of spin j couple to $j-1$ of the last particle, not j .

A recent calculation by Rakavy (29) based on the Nilsson rotational model predicts $3/2^+$ for the O^{19} ground state. It is by no means certain from this calculation, however, that the O^{19} nucleus is deformed. Furthermore, if the O^{19} nucleus were deformed the calculation could be made to yield a $5/2^+$ ground state.

It is felt, therefore, that the evidence for the $5/2^+$ designation outweighs the theoretical possibility of $3/2^+$ and that the ground state of O^{19} is the $5/2^+$ state predicted by the shell model calculations.

First excited state (0.096-Mev).—The first excited state of O^{19} is identified as the $3/2^+$ state predicted by theory.

Zimmerman (13) notes that the 1.470-Mev level (definitely $1/2^+$) decays preferentially to the 0.096-Mev level rather than to the $5/2^+$ ground state. This suggests that since an E2 transition is allowed to the ground state, the preferential transition to the 0.096-Mev level is either E1 or M1. These dipole transitions allow the 0.096-Mev level to have a $1/2^\pm$ or $3/2^\pm$ character.

In a separate experiment, Zimmerman (13) was able to measure a lifetime of $1.75 (1 \pm 0.16) \times 10^{-9}$ seconds for the decay of the 0.096-Mev level to the ground state. Since this lifetime is of the right order of magnitude for a slow E1 or M1 transition to the ground state, this suggests $J = 3/2, 5/2, \text{ or } 7/2$ for the 0.096-Mev level. The overlap between these values and those gotten from the preferential decay data yields $J = 3/2^\pm$ as the level designation.

On the assumption that the 0.096-Mev level is the $3/2^+$ state predicted by theory, Zimmerman calculated the lifetime for a pure

M1 transition using the Elliott and Flowers wave functions. This computed lifetime of 2.2×10^{-9} seconds agrees well with his measured lifetime of 1.75×10^{-9} seconds.

This same assumption as to the $3/2^+$ designation was employed in this investigation to calculate the theoretical reduced width of the 0.096-Mev state relative to the $5/2^+$ ground state. The value of 0.055 (from the Elliott and Flowers wave functions) agrees reasonably well with the measured relative reduced width of 0.040. The value of 0.003 calculated from the Redlich wave functions does not agree. An examination of Table V-1 (a) and (b) shows that in the Redlich case not only is the appropriate Type 1 configuration admixture in the $O^{19} 3/2^+$ state less by a factor of 3 than in the Elliott and Flowers case, but also that the O^{18} parent for the Redlich admixture is less by a factor of 5 than the O^{18} parent for the Elliott and Flowers admixture. It is apparent that a slight adjustment in the Redlich parameters could restore the balance between the two predictions. (An additional calculation using wave functions given by Redlich in Table IV of (7) which result from a deformed nucleus model yields a value, for example, of 0.088 for the relative reduced width of the $3/2^+$ state.)

The analysis of Ahnlund's angular distribution study (at $E_d = 0.8$ -Mev) of the first excited state by Popic—mentioned in Chapter

IV—suggests a designation of $1/2^-$ or $3/2^-$ for the state. But, in view of the fact that the Coulomb barrier for O^{19} is ~ 3 -Mev, the low deuteron energy of 0.8-Mev makes the angular distribution analysis considerably more complex and less trustworthy than at higher deuteron energies.

The 0.096-Mev state is therefore designated as the $3/2^+$ state predicted by Elliott and Flowers and by Redlich.

Second excited state (1.470-Mev).—This state is clearly the $1/2^+$ state predicted by theory.

Reference to Table V-3 shows that the theoretical and experimental relative reduced widths differ by more than a factor of 2. This is not particularly disturbing because of two factors.

First, there exists the possibility—which has already been pointed out—that because of the limitations inherent in the Butler theory the experimental relative reduced width may be in error. Bilaniuk and Hough (17) find, for example, that a semi-empirical treatment of their $l_n = 2$ and $l_n = 0$ angular distributions in O^{18} leads to a reduced width ratio that differs by ~ 30 percent from the Butler theoretical treatment.

Second, a few modest changes in the weights of the configurations which form the O^{18} ground state and the O^{19} ground state

allow the theoretical relative reduced width to be brought into better agreement with the existing experimental value. For example, by changing the weight of the $(5/2)^2$ configuration in O^{18} from 74 percent to 65 percent (which is equivalent to changing the amplitude from 0.86 to 0.80) and by changing the weight of the $(5/2)^3$ configuration in O^{19} from 72 percent to 50 percent (which is equivalent to changing the amplitude from 0.85 to 0.71) the relative reduced width is increased from 1.72 to 2.32. Changes such as these might be necessitated, for example, by the introduction of core excited configurations which will be discussed in connection with the odd parity 3.94-Mev state or by a change in the exchange mixture of the interparticle potential which will be discussed in connection with the excitation energies of the low-lying O^{19} states.

3.14-Mev state.—The existence of this $1/2^+$ state, in addition to the $1/2^+$ state at 1.470-Mev, was not predicted either by Elliott and Flowers or by Redlich. This is reasonable in view of the self-imposed restriction in the two calculations to consider states at low excitation energy constructed primarily from Type 0 configurations.

This state may be qualitatively understood by considering states in the energy region above the region of Type 0 states to be constructed from Type 1 configurations with small Type 0 and Type 2 configuration admixtures. Because the predominant Type 1 configurations have no parents in the O^{18} ground state, these states can be formed by stripping only through the appropriate Type 0 and Type 2 admixtures. It is found that a postulated 10 percent admixture of Type 0 configuration in a predominantly Type 1 state is adequate to account for the observed stripping intensity to this state.

It is felt, therefore, that in a qualitative way the existence and construction of the 3.14-Mev state can be understood in the level structure of O^{19} . It is, of course, a little surprising to find a Type 1 state some 2-Mev below the region around 5-Mev, which is usually considered the Type 1 domain.

3.94-Mev state.—This state is an odd parity state and because of its $1/2^-$ or $3/2^-$ designation, can be understood qualitatively in terms of the excitation of the doubly-magic O^{16} core.

In order to observe such a state by stripping, configuration admixtures appropriate to core excitation must be added not only to the ground state wave function of O^{18} , but also to the wave function

characterizing the O^{19} state. Thus, configurations of the form $(d_{5/2})^4(p_{1/2})^{-2}$ and $(d_{5/2})^4(p_{3/2})^{-2}$ and also the less likely configurations $(d_{5/2})^2(s_{1/2})^2(p_{1/2})^{-2}$ and $(d_{5/2})^2(s_{1/2})^2(p_{3/2})^{-2}$ are admixed into the O^{18} ground state wave function. These configurations simply express the fact that two neutrons are removed from the p shell and—coupled to zero—are placed in either the $d_{5/2}$ level or $s_{1/2}$ level, thus leaving two holes—also coupled to zero—in either the $p_{1/2}$ level or $p_{3/2}$ level. On this basis, then, $1/2^-$ and $3/2^-$ O^{19} states can be constructed from configurations of the form $(d_{5/2})^4(p_{1/2})^{-1}$ and $(d_{5/2})^2(s_{1/2})^2(p_{1/2})^{-1}$; and $(d_{5/2})^4(p_{3/2})^{-1}$ and $(d_{5/2})^2(s_{1/2})^2(p_{3/2})^{-1}$, respectively, which can be reached by a stripping reaction on the O^{18} ground state through the capture of an $l_n = 1$ neutron into one of the p-shell vacancies.

No decision between a $1/2^-$ or $3/2^-$ designation for this state can be made on the basis of existing evidence.

$7/2^+$ and $9/2^+$ states.—The $7/2^+$ and $9/2^+$ states predicted to lie at an excitation energy of ~ 1.75 -Mev by Elliott and Flowers (Redlich did not give the excitation energies of these states) were not observed in this investigation.

An examination of the admissible Type 0 configurations $[(5/2)^2 1/2$ only for the $7/2^+$ state, $(5/2)^2 1/2$ and $(5/2)^3$ for the

$9/2^+$ state] and the Type 1 and Type 2 admixtures used to construct these two states shows that no three particle configuration having a spin of $7/2^+$ or $9/2$ and constructed entirely from s-d shell nucleons can be reached via the (d,p) stripping reaction on the 0^+ ground state of O^{18} . [$(3/2)^3$ leads to $J = 3/2$ only.]

In order to observe a $7/2^+$ or $9/2^+$ state by $O^{18}(d,p)O^{19}$ an $l_n = 4$ ($j_n = 4 \pm 1/2$) neutron would have to strip to an admixed configuration of the form $(5/2)_0^2 \times 7/2$, $(5/2)_0^2 \times 9/2$, et cetera. In view of the low intrinsic g stripping rate and the separation of the 1g and 1d-2s shells, it seems unlikely that the weights of such admixed configurations necessary to give observable stripping intensities could be realized.

It appears, therefore, that a search for the $7/2^+$ and $9/2^+$ states predicted by Elliott and Flowers and by Redlich must utilize reactions other than stripping.

Observed and theoretical excitation energies

It is apparent that the predicted positions of the $3/2^+$ and $1/2^+$ states (see Fig. V-1) do not agree with experiment.

Elliott and Flowers point out that the $T = 3/2$ states of O^{19} are more sensitive to changes in the exchange mixture of the inter-particle interaction than the $T = 1/2$ states of F^{19} . Thus, they feel

that the level structure of O^{19} could be brought into better agreement with experiment by varying the exchange mixture without, at the same time, disturbing the good agreement between the calculated and observed F^{19} level structure. A similar change could also be applied to the Serber mixture employed by Redlich who also gets good agreement between the calculated and observed F^{19} level structure.

Summary and recommendations for future work

The theoretical treatments of the level structure of O^{19} by Elliott and Flowers and by Redlich are qualitatively in agreement with the results of this investigation. Further, it appears that reasonable qualitative extensions of these treatments to include Type 1 configuration states and core-excited states are able to incorporate the $1/2^+$ state at 3.14-Mev and the $1/2^-$ or $3/2^-$ state at 3.94-Mev into the O^{19} level structure. Quantitatively, however, there is a severe disagreement between theory and experiment regarding the excitation energies of the Type 0 $1/2^+$ and $3/2^+$ states; the Type 1, 3.14-Mev state seems ~2-Mev too low.

Unfortunately, the manipulation of the exchange mixture in the interparticle interaction to give the correct excitation energies of low-lying O^{19} states; the addition of core-excited configurations to describe the odd parity states; and the introduction of predominantly

Type 1 and Type 2 configurations to describe states at higher excitation energies demand extensive calculations for mass 19 nuclei. Also, because of the similarity between the predictions of the deformed nuclear model calculations of Rakavy (29) and Redlich (7) and the shell model calculations of Elliott and Flowers (5) and Redlich (6, 7) for mass 19 nuclei, additional collective model calculations might provide valuable insight into the structure of F^{19} and O^{19} .

Such an effort is probably not warranted, however, until the experimentally observed level structure of O^{19} is comparable in detail to the known structure of F^{19} . One of the future experimental studies should be a search for the $7/2^+$ and $9/2^+$ states; this information would—~~together~~ with a further study of the weak 0.096-Mev level which has been designated as the $3/2^+$ state—complete the experimental picture of the even parity states of predominantly Type 0 configurations predicted by the existing theories. Other detailed experimental investigations of the O^{19} level structure up to ~ 10 -Mev excitation would supply the information needed for the theoretical treatments proposed in the preceding paragraph.

APPENDIXES

APPENDIX A

NUCLEAR SPECTROSCOPIC SCANNING

Human scanning

The nuclear emulsion plates which detect the (d,p) reaction protons are carefully positioned at the image plane of the magnetic analyzer and tipped at an angle of 45° with respect to the image plane. This is illustrated in Fig. A-1. In order to prevent

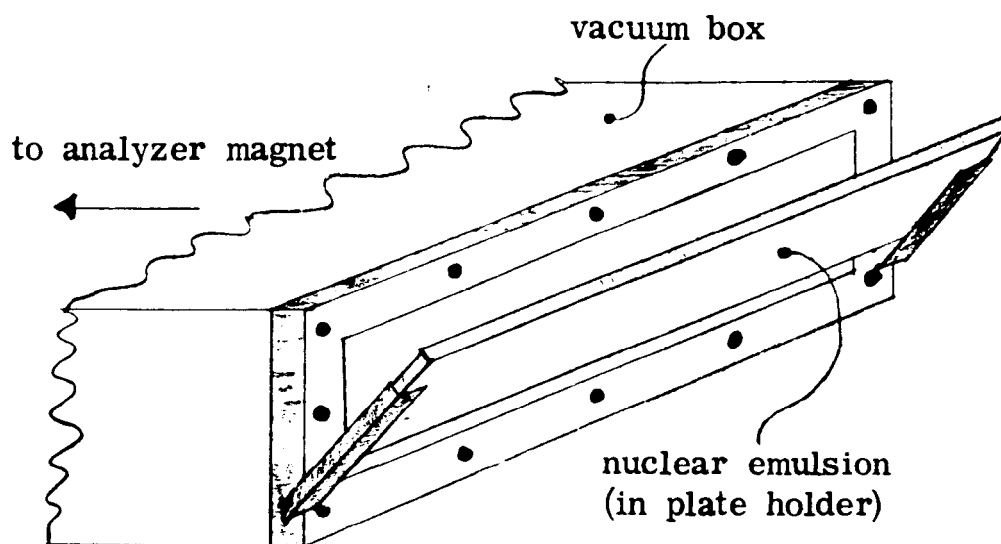


Figure A-1.—Image plane—nuclear emulsion geometry.

unwanted particles, particularly deuterons, from penetrating the emulsion and being recorded, absorber (typically, aluminum or lead) is placed over the emulsion surface.

Unfortunately, not all tracks observed in a given microscopic field of view are necessarily acceptable. Some unacceptable tracks arise from protons which have scattered off slits or duct-work between the scattering chamber and the nuclear emulsion plate and whose recorded position in the emulsion bears no relationship to their momentum. Other protons originate in the emulsion itself. These knock-on or recoil protons are the result of collisions between fast neutrons (a major component of cyclotron background) and the hydrogen atoms of the emulsion. In cases of low Q (d,p) reactions, particularly at reaction angles near 0° , deuteron tracks may enter the emulsion because sufficient absorber to prevent deuteron penetration cannot be used without stopping acceptable protons.

Consequently, a certain amount of track analysis is required in nuclear spectroscopic scanning, although not of a high degree of complexity, before tracks can be counted.

The technique which has been adopted is to scan the emulsion in depth. Reference to Fig. A-1 indicates that an acceptable reaction proton should penetrate the emulsion at a dip angle of 45° . When such a track is observed with a microscope having a

magnification of 200 $\times$ and a depth of field in focus that is approximately one-third the developed emulsion thickness (50μ), it has the appearance of the track shown in the photograph of Fig. III-2. By changing the focus setting of the microscope, the slice of the emulsion in focus shifts and hence, different segments of the total track come into focus. Thus, the entire length of the track can be examined.

Acceptable tracks are those which: begin at the top surface of the emulsion (this eliminates knock-ons), penetrate the entire emulsion thickness (this eliminates deuterons), have a projected length appropriate to a dip angle of $\sim 45^\circ$, and are within an angle of $\sim 30^\circ$ relative to the vertical (these last two requirements eliminate most scattered protons).

Machine scanning

A considerable saving in the complexity of the machine scanner design was initially obtained by the adoption of a two-dimensional scanning procedure. That is, the machine track analysis was based upon the examination of one emulsion slice held at some specified depth in the emulsion rather than on the basis of the correlated emulsion slices employed in the human track analysis.

This means, however, that several of the track acceptance criteria can no longer be imposed.

In retrospect, it has been possible to minimize the effect of deuteron surface contamination by selecting the depth at which the machine scans beneath the deuteron blanket. In cases where this technique has not proved feasible, the contamination has been removed by vigorously rubbing the emulsion with methyl alcohol (CH_3OH) to dissolve the surface layers.

Comparable circumvention or removal techniques cannot be applied to knock-on proton contamination since these tracks can and do appear at all emulsion depths. This has not limited machine performance, however, because normally the background level due to knock-ons is low.

Thus, an acceptable track for the machine scanner would lie within an angle of $\sim 30^\circ$ with respect to the vertical and be longer than some minimum length.

The elimination of scanning in depth has the advantage, in addition to the saving effected in machine complexity, that because a given area of nuclear emulsion is examined only once at the selected depth, the scanning time is reduced considerably. In the existing machine scanner, sixty fields of view are analyzed per second.

APPENDIX B

THE TRACK ANALYSIS SYSTEM

Rejection of normal background grains or equivalently, the standardized video pulses representing these grains, is based upon their random distribution in time in the line-by-line video output. The pulses associated with track grains, however, are correlated in time. For a track oriented at exactly 90° with respect to the scanning raster, these standard video pulses are separated from each other by precisely $63.5\mu\text{sec}$, the horizontal scan time. Tracks which deviate from the vertical lead to slightly modified separation values. For example, a track which deviates from the vertical by $\pm 45^\circ$ changes the time separation by $\Delta t = \mp 0.15\mu\text{sec}$. The problem of track analysis is, therefore, one of testing all the standardized video output pulses for a sequence of pulses each one of which is separated from its nearest neighbor by $63.5 \pm \Delta t \mu\text{sec}$. Note that the selection of Δt determines the maximum acceptance angle a track can have.

The circuitry which performs the track analysis is illustrated in Fig. B-1. A block diagram is given in Fig. B-2. The output

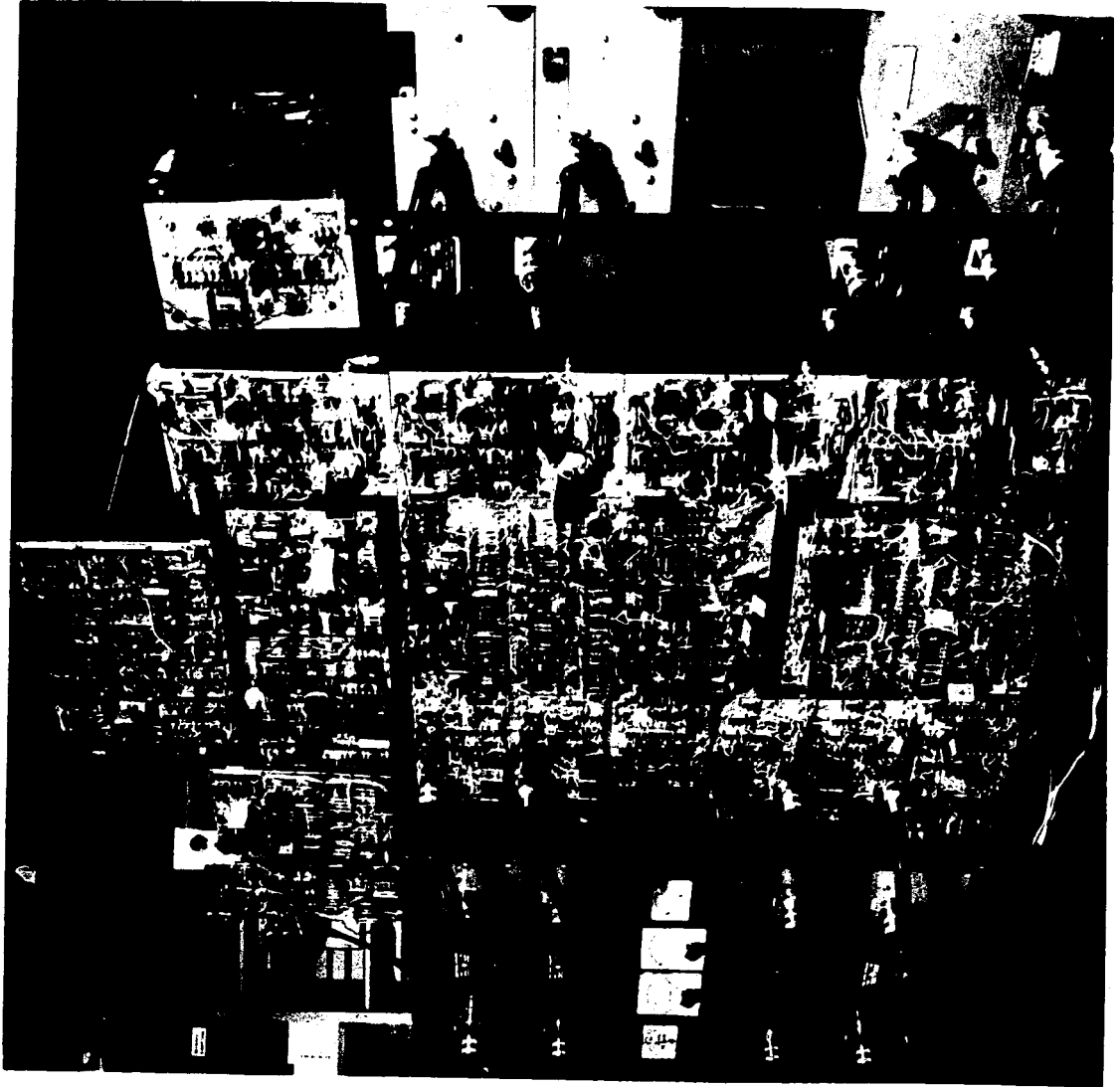


Figure B-1.—Track analysis system.

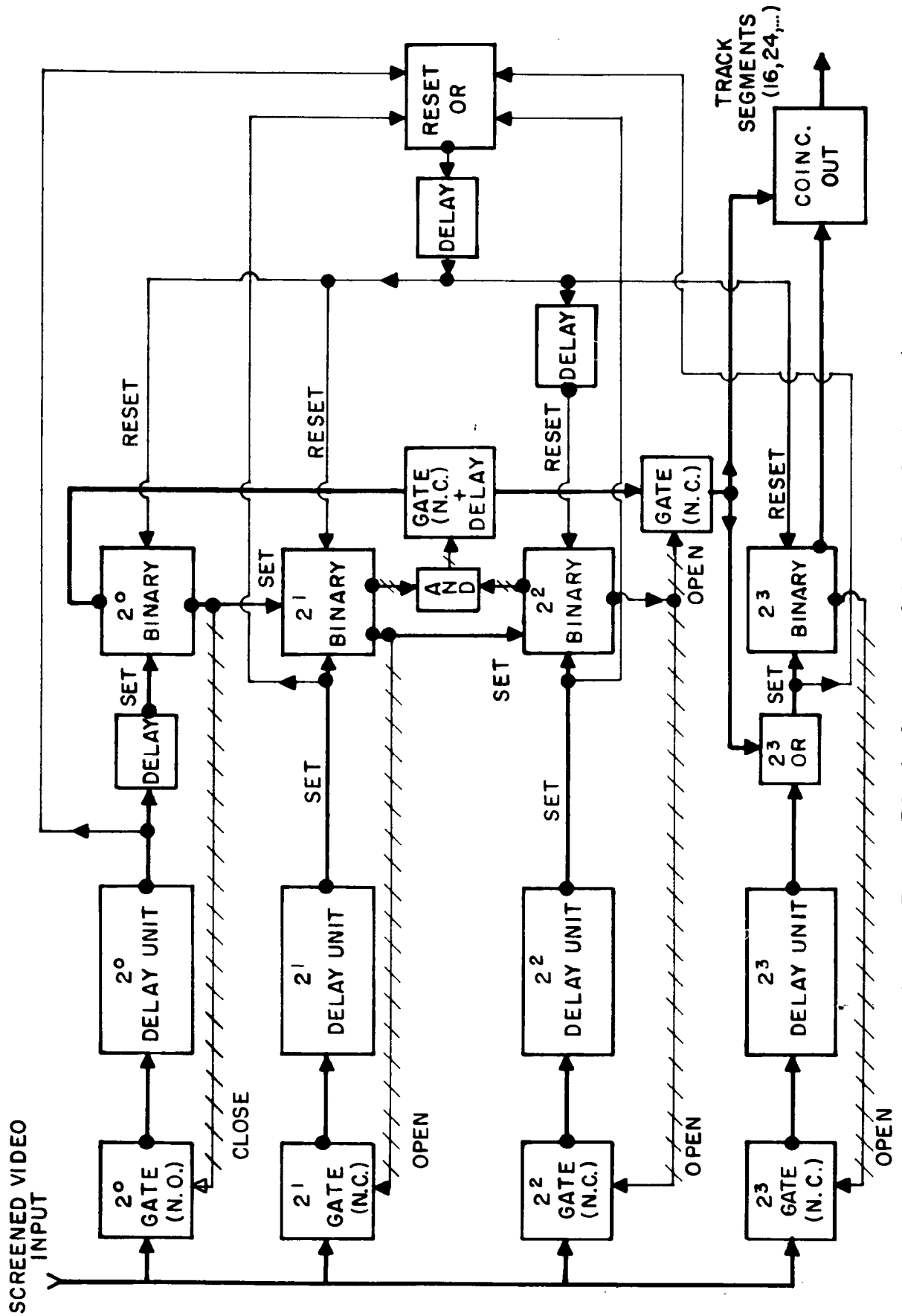


Figure B-2.—Block diagram of track analysis system.

pulses from the width discriminating system are presented to the four Gates which are coupled to four fast ($0.1\mu\text{sec}$ resolving time) Binaries such that, with all the Binaries, in a RESET state (2^0 flipped, 2^1 , 2^2 , and 2^3 flopped), only the 2^0 Gate is open. Under these circumstances a pulse is admitted to the 2^0 Delay Unit. This unit (like the remaining three units) consists of: a pulsed oscillator (21) which, when triggered, delivers a damped pulse of 40-mc rf to a crystal transducer; a quartz ultrasonic delay line of $\sim 63\mu\text{sec}$ (slightly less than the horizontal scan time) length; a second crystal transducer followed by 40 db of wide-band amplification; and finally, a detector followed by further amplification and pulse shaping. The delayed pulse goes to the Reset OR circuit (any one OR any combination of four input pulses will yield an output pulse) and also, after a further short delay, this pulse SETS (flops) the 2^0 Binary. The output pulse from the flopping 2^0 Binary SETS (flips) the 2^1 Binary. The situation is such that, until all the Binaries are RESET by the delayed RESET pulse, the 2^0 Gate is CLOSED and the 2^1 Gate is OPEN. A second pulse from the video appearing in this interval between the Binary SET and the delayed Binary RESET is admitted only to the 2^1 Delay Unit. After the 2^1 delay it initiates a delayed RESET pulse and also SETS (flips) the 2^1 Binary. The situation in the SET-RESET interval is: 2^0 Gate OPEN and 2^1 Gate OPEN. A

third pulse, if present in this interval, is admitted to both the 2^0 and 2^1 Delay Units. The delayed 2^1 pulse then SETS (flips) the 2^1 Binary, the delayed 2^0 Pulse, after its additional short delay, SETS (flips) the 2^0 Binary thus RESETTING (flopping) the 2^1 Binary which in turn SETS (flips) the 2^2 Binary. (The additional short delay preceding the 2^0 Binary, thus, permits the 2^1 Binary to SET before being RESET by the 2^0 Binary output pulse in cases such as this when SET pulses are due to arrive at both Binary units.) A fourth pulse in this SET-RESET interval is therefore admitted to the 2^2 Delay Unit only, which signifies the fact that $4 (0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 0 \times 2^0 = 4)$ consecutive successful correlations have been established.

Thus, the memory of the number of consecutive successful correlations that will have been established with the acceptance of a given pulse in the SET-RESET interval is established entirely by that pulse in the particular combination of Gates through which it passes.

Since each input pulse is responsible for the initiation of the SET-RESET interval for a following correlated pulse, moderately curved tracks are capable of being followed and sifted by the analysis circuit. Further, the RESET action of a pulse, in restoring the four Gates to their quiescent status, rapidly frees the analysis

circuit to test additional screened video pulses for track correlations.

The appearance of a gap in a track (which might be caused by a local nonuniform silver bromide distribution in the emulsion gelatin) allows what correlation information has been established to disappear since no pulse is present in the SET-RESET interval to "carry" the memory. Such an occurrence necessitates a fresh start with the remainder of the track. But, this is a necessary consequence of the circuit function of rejecting uncorrelated pulses (i.e., those not separated by $63.5 \pm 4t_{\mu\text{sec}}$).

In order to help avoid this gap difficulty a cylindrical eyepiece lens of modest strength is used in addition to the normal eyepiece of the microscope. The resultant astigmatic optical system has the property of transforming the image of a grain from a spot into a stubby, vertical line. This acts as an artificial gap filler for tracks and helps prevent this loss of correlated information. In practice it has not been found to introduce large-scale pseudo correlations between uncorrelated background grains.

The analysis of the circuit operation for a track composed of more than four video pulses (usually of the order of 30-60 video pulses) is an extension of this four-pulse track example but with several additional complicating factors. The most obvious

addition is the normally closed (N.C.) gate fed by the 2^0 Binary which is opened only when both the 2^1 Binary and the 2^2 Binary are in the SET state. Its purpose is to feed forward the eighth pulse, say, directly to the 2^3 Binary and thus avoid the accumulated carry time (the delay between the input and output of a transitioning Binary) inherent in the more usual path via the 2^1 and 2^2 Binaries. Other additions which also deal with delicate timing relationships are concealed, however, in such matters as pulse shapes, the use of leading or trailing edges in triggering and similar considerations. A full analysis would demand, therefore, explicit discussion of individual circuit components.

The net result of such an analysis is that Track Segment pulses are generated by the Output Coincidence circuit at the sixteenth, twenty-fourth, thirty-second, ... consecutive correlated video input pulse for each track tested.

APPENDIX C

REACTION KINEMATICS

Calculations of E_2 vs. θ (for values of θ from 0° to 110° in 5° increments) have been performed by an IBM 650 for a series of deuteron-induced reactions using the expression (30),

$$\sqrt{E_2} = \frac{(M_1 M_2)^{1/2}}{M_2 + M_3} \sqrt{E_1} \cos \theta + \sqrt{\frac{M_3}{M_2 + M_3} Q + \frac{M_3 - M_1}{M_2 + M_3} E_1 + \frac{M_1 M_2}{(M_2 + M_3)^2} E_1 \cos^2 \theta} \quad (C-1)$$

where:

M_1 = mass of bombarding particle

M_2 = mass of reaction particle

M_3 = mass of residual nucleus

E_1 = laboratory energy of bombarding particle

E_2 = laboratory energy of reaction particle

θ = laboratory reaction angle

Q = reaction energy

The machine program also included calculations of $(\partial E_2)/(\partial E_1)$ and $(\partial E_2)/(\partial Q)$ for the same angular values. All calculations were based upon a deuteron beam energy of 7.771-Mev.

Curves of E_2 vs. θ for the proton groups from O^{19} and from significant contaminant nuclei were plotted from the machine results; these curves are given in Fig. C-1.

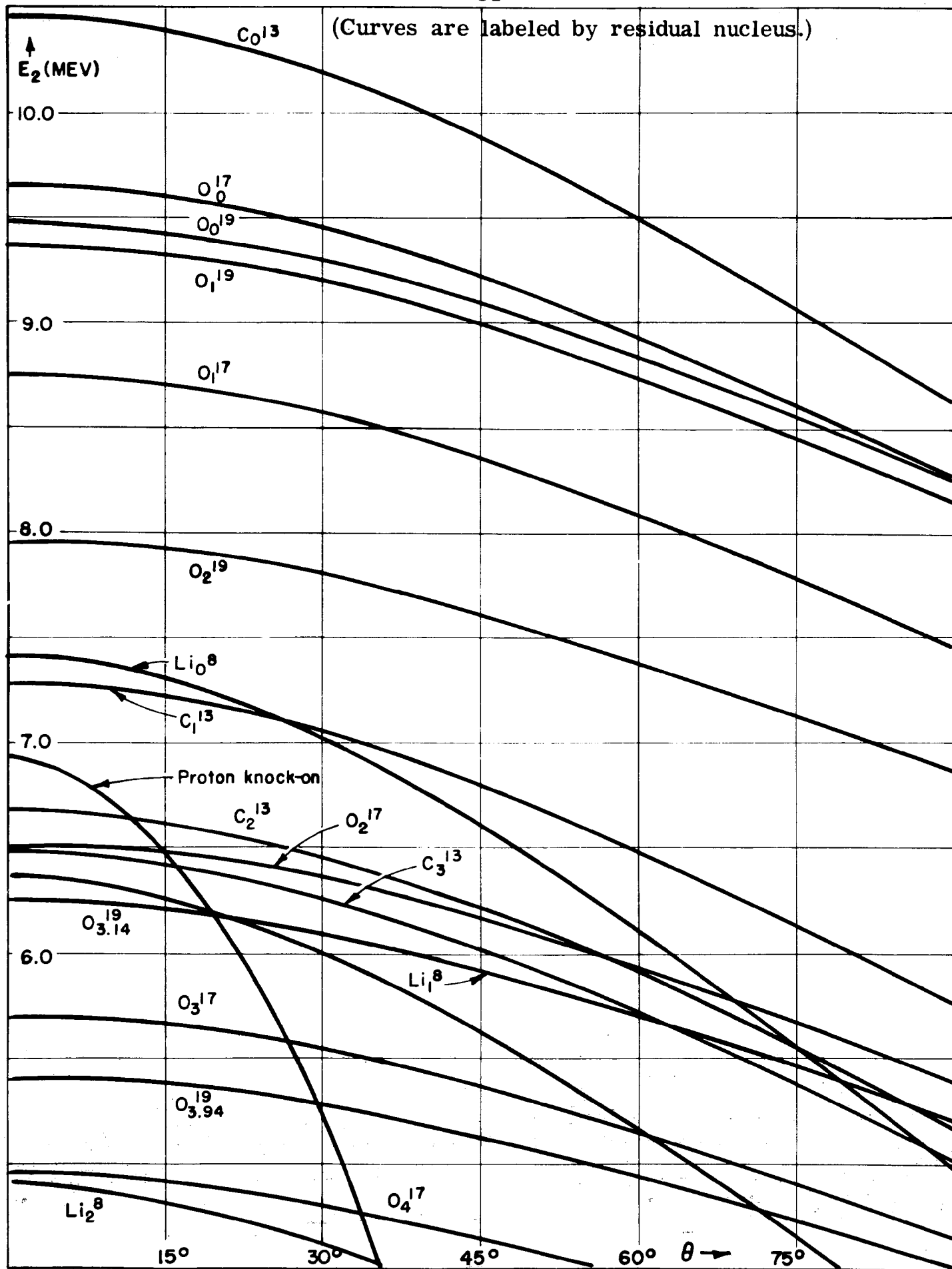


Figure C-1.—(d,p) Kinematics.

REFERENCES

1. M. G. Mayer and J. H. D. Jensen, Elementary Theory of Nuclear Shell Structure (John Wiley and Sons, Inc., 1955).
2. M. G. Mayer, Phys. Rev., 75, 1969 (1949).
3. O. Haxel, J. H. D. Jensen, and H. E. Suess, Phys. Rev., 75, 1766 (1949), and Zeit. f. Physik, 128, 295 (1950).
4. M. G. Mayer, Phys. Rev., 78, 16 (1950).
5. J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London), A229, 536 (1955).
6. M. G. Redlich, Phys. Rev., 99, 1427 (1955).
7. M. G. Redlich, Phys. Rev., 110, 468 (1958).
8. S. T. Butler, Proc. Roy. Soc., 208, 559 (1951).
9. J. S. King and W. C. Parkinson, Phys. Rev., 88, 142 (1952).
10. R. Huby, Prog. Nuc. Phys., 3, 177 (1953).
11. K. Ahnlund and C. Mileikowsky, Arkiv f. Fysik, 8, 161 (1954).
C. Mileikowsky and K. Ahnlund, Phys. Rev., 96, 996 (1954).
H. D. Holmgren, T. D. Hanscome, and D. K. Willett, Phys. Rev., 98, 241A (1955).
J. Thirion, R. Cohen, and W. Whaling, Phys. Rev., 96, 850A (1954).
12. T. F. Stratton, J. M. Blair, K. F. Famularo, and R. V. Stuart, Phys. Rev., 98, 629 (1955).
13. W. Zimmerman, Jr., Phys. Rev., 114, 837 (1959).
14. O. M. Bilaniuk, "The Structure of O¹⁸" (unpublished Ph.D. dissertation, Dept. of Physics, University of Michigan, 1957).

15. D. R. Bach, W. J. Childs, R. W. Hockney, P. V. C. Hough, and W. C. Parkinson, *Rev. Sci. Instr.*, 27, 516 (1956).
16. W. C. Parkinson (private communication).
17. O. M. Bilaniuk and P. V. C. Hough, *Phys. Rev.*, 108, 305 (1957).
18. H. Taube, *An. Rev. Nuc. Sci.*, 6, 277 (1956).
19. L. H. Th. Rietjens, O. M. Bilaniuk, and W. C. Parkinson, *Rev. Sci. Instr.*, 29, 768 (1958).
20. G. M. Glasford, *Fundamentals of Television Engineering* (McGraw-Hill Book Company, Inc., 1955), Chaps. 1, 4, 12, and 14.
21. P. V. C. Hough, J. A. Koenig, and W. Williams, *Electronics*, 32, 58 (March 27, 1959).
22. K. Ahnlund, *Arkiv f. Fysik*, 11, 379 (1957).
23. F. Ajzenberg-Selove and T. Lauritsen, *Nuc. Phys.*, 11, 1 (1959).
24. D. M. Van Patter and W. Whaling, *Rev. Mod. Phys.*, 29, 757 (1957).
25. C. R. Lubitz, "Numerical Table of Butler-Born Approximation Stripping Cross Section" (Randall Laboratory of Physics, University of Michigan, 1957).
26. R. V. Popic, *Nuovo Cimento*, 4, 1597 (1956).
27. K. Ahnlund, *Arkiv f. Fysik*, 10, 425 (1956).
28. J. B. French and B. J. Raz, *Phys. Rev.*, 104, 1411 (1956).
29. G. Rakavy, *Nuc. Phys.*, 4, 375 (1957).
30. A. B. Brown, C. W. Snyder, W. A. Fowler, and C. C. Lauritsen, *Phys. Rev.*, 82, 159 (1951).