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ANNUAL PROGRESS REPORT
FOR PERIOD ENDING DECEMBER 31, 1962

OAK RIDGE NATIONAL LABORATORY

operated by

UNION CARBIDE CORPORATION

for the

U.S. ATOMIC ENERGY COMMISSION

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For Period Ending December 31, 1962

Robert S. Livingston, Director
Alexander Zucker, Associate Director

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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Summary

Heavy-ion reactions in the low-Z region were investigated with 27-Mev nitrogen ions from the 73-Inch Cyclotron and with 30-Mev oxygen ions from the Tandem Van de Graaff. Experiments included studies of angular distributions and excitation functions for transfer reactions, compound-nucleus reactions, effects of angular momentum on the density of nuclear states, and so-called Ericson fluctuations in the compound nucleus Si^{28} .

Nuclear reactions induced with 22-Mev protons in the 86-Inch Cyclotron were used in studies of the pickup-reaction mechanism, shell-model studies from pickup reactions, scattering and the optical model, and level schemes in highly deformed nuclei.

In theoretical investigations of the mechanisms of nuclear reactions and related nuclear-structure information, the elastic scattering of complex particles was analyzed via the optical model; the applicability of the distorted-wave method to stripping reactions was investigated, and the inelastic scattering of carbon ions from carbon was examined.

Experimental studies with the eight-sector electron model, Analogue II, led to very successful deflection of the beam in November 1962, a

significant advance in accelerator technology. This investigation, still incomplete, eases one of the major uncertainties associated with the proposed Mc^2 cyclotron. The radioactivity resulting from the residual undeflected beam being dumped onto the structure of the cyclotron can now be estimated much more reliably.

Successful test operation of the Oak Ridge Isochronous Cyclotron (ORIC) at full radius in March 1962 verified the design of the azimuthally varying magnetic field, which is expected to provide for fixed-frequency operation for proton energies up to 75 Mev. During these test operations at 8 Mev, the properties of the beam at full radius were explored, and the beam was brought through an electrostatic deflector channel. The machine was then shut down for the installation of the full-power rf system and the beam-extraction components.

Investigation of basic problems connected with the design of large magnets with Nb-Zr superconductors was continued. It was found that the use of a copper secondary, bifilar wound with the superconductor, and the use of epoxy casting, to rigidly confine the windings, markedly increase the current capacity of the magnet and eliminate the damage usually encountered when the superconductor goes normal.

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1. Heavy-Particle Physics

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The study of heavy-ion reactions in the low- Z region included experiments on transfer-reaction excitation functions and angular distributions, compound-nucleus reactions, the effect of angular momentum on the density of nuclear states, and the investigation of so-called Ericson fluctuations in the compound nucleus Si^{28} . In addition, new scattering chambers and other equipment were designed and built for use on ORIC. During six weeks of running time on the tandem accelerator, an O^{16} beam was used for various experiments. The ORNL 63-Inch Cyclotron was reactivated occasionally for N^{14} bombardments.

EXCITATION FUNCTIONS

During the past year an extensive program was carried out in determining excitation functions for reactions induced by 27.5-Mev N^{14} ions. The excitation functions were determined by the usual method of bombarding thick targets at various energies. The resultant products were identified, and their decay was followed by the use of a calibrated NaI crystal spectrometer. In most instances no chemical separations were necessary, since the radioactive products could be identified unambiguously simply by means of their half-lives and gamma radiations. Twenty-two excitation functions were obtained in three rather separate investiga-

tions: (1) the determination of cross sections for reactions proceeding through a compound-nucleus stage; (2) the investigations of isomeric yield ratios for Sc^{44m} and Sc^{44g} as produced by the N^{14} bombardment of P^{31} , S^{32} , and Cl^{35} ; and (3) the study of single-nucleon transfer-reaction cross sections.

Compound-Nucleus Reactions

The production of the following nuclides from various target nuclei was investigated: Ne^{23} from B^{11} ; P^{30} from F^{19} ; K^{38} from Al^{27} ; Cl^{34m} and K^{38} from silicon; Sc^{43} , Sc^{44m} , and Sc^{44g} from P^{31} ; Sc^{43} , Sc^{44m} , and Sc^{44g} from S^{32} ; Sc^{43} , Sc^{44m} , Sc^{44g} , Ti^{45} , and V^{47} from Cl^{35} ; and Cr^{49} from Cl^{37} . Owing to the lack of space, only the chlorine results are shown in Fig. 1.1, particularly since the ensuing discussion is limited to reactions resulting from the bombardment of Cl^{35} .

Cross sections were measured for the production of four isotopes from the N^{14} bombardment of Cl^{35} , that is, V^{47} , Ti^{45} , Sc^{44} , and Sc^{43} . These experimental data from final isotopes resulting from one compound nucleus (Cr^{49}) can be compared with the predictions of the statistical theory. The theory of the emission of particles from an excited compound nucleus is originally due to Weisskopf.⁵ Recently, in a series of papers Dostrovsky *et al.*⁶

¹Research participant, University of Tennessee.

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⁴Physics Division (collaborated on resonances in $\text{C}^{12} + \text{O}^{16}$).

⁵V. F. Weisskopf, *Phys. Rev.* **52**, 295 (1937).

⁶I. Dostrovsky, Z. Fraenkel, and G. Friedlander, *Phys. Rev.* **116**, 683 (1959); I. Dostrovsky, Z. Fraenkel, and L. Winsberg, *Phys. Rev.* **118**, 781 (1960); and I. Dostrovsky, Z. Fraenkel, and P. Rabinowitz, *Phys. Rev.* **118**, 791 (1960).

Fig. 1.1. Excitation Functions for Reactions Induced by N^{14} Ions on Chlorine.

described a Monte Carlo calculation based on this theory. Their calculations incorporate an analytic form for the inverse cross section chosen to approximate square-well potential cross sections. The form of the level density does not contain a $1/E^2$ term; neither gamma-ray de-excitations nor angular momentum effects are considered. In addition, no attempt is made to include the effects of nuclear clusters on the initial stages of the cascade. An IBM 7090 program essentially duplicating this approach has become available at ORNL. This program was utilized to determine the applicability of the Monte Carlo calculations in their present form for the compound system of N^{14} and Cl^{35} .

A search on the level-density parameter a was made to determine the value best fitting the data, for an incident energy of 27 Mev. It was found that the predicted ratios did not agree with the experimental ratios for any value of a . The best agreement was found, however, when a was equal to 1.70. The experimental and theoretical cross-section ratios are compared in Table 1.1.

The reason for the poor agreement and the necessity for a low value of a arises from the fact that the Monte Carlo calculations predict very few emitted alphas in comparison with neutrons and protons. The experimental data, on the other hand,

clearly show that alpha emission competes successfully with neutron and proton emission. Thus, the dearth of predicted alpha emission is responsible for the lack of agreement with experiment. In addition, it is found that the number of emitted alphas has a maximum for $a \sim 1.70$. This is the reason why it is necessary to select a low value to obtain the best fit with experiment.

The value of a best reproducing the data, excluding the regions near magic numbers, is usually $a \sim A/10$. One of several possible explanations for the appearance of a small value of the level-density parameter and the poor agreement between theoretical and experimental cross-section ratios is the absence of an E^{-2} term in the level-density expression.

The Monte Carlo calculations were modified to include this type of level density, and a search on a was used to determine the best value. As before, the overall agreement is very poor, with the best fit occurring at $a \sim 5.0$. The values obtained are also shown in Table 1.1.

One additional modification was made in the original program. This was the replacement of the analytic form of the inverse cross sections by corresponding cross sections calculated from optical-model transmission coefficients. It was found that this increased the predicted number of nuclei formed by alpha emission by $\sim 15\%$. This effect, however, is insufficient to account for the discrepancy between the experimental data and the statistical-model calculations.

Isomer Yield Ratios

The isomer yield ratio Sc^{44m}/Sc^{44g} for the production of Sc^{44} from the reactions $P^{31}(N^{14},p)Sc^{44}$, $S^{32}(N^{14},2p)Sc^{44}$, and $Cl^{35}(N^{14},\alpha p)Sc^{44}$ was determined. These ratios are shown in Fig. 1.2, plotted as a function of $E_{c.m.}$. The steady, sharp increase of the ratio with bombarding energy for P^{31} and S^{32} is consistent with the Sc^{44} being produced by means of a compound-nucleus mechanism. As the energy and the angular momentum brought into the compound nucleus are increased, the probability of the residual nucleus being left in a state of higher angular momentum also increases and the ratio is thus expected to increase. The Cl^{35} ratio, on the other hand, rises gently and then levels off at ~ 18.6 Mev. This behavior can be explained in two ways. First, the loss from the compound system (Cr^{49}) of a large amount of angular momentum,

Table 1.1. Experimental and Theoretical Cross-Section Ratios^a for Reactions Resulting from the Bombardment of Cl³⁵ by N¹⁴

Products	Experimental	Theoretical Without $1/E^2$ ($a = 1.7$)	Theoretical With $1/E^2$ ($a = 5.0$)
$\frac{\text{Sc}^{44} (ap)}{\text{V}^{47} (pn)}$	1.18 ± 0.28	0.27 ± 0.01	0.26 ± 0.05
$\frac{\text{Sc}^{44} (ap)}{\text{Ti}^{45} (a)}$	20.0 ± 4.74	13.1 ± 2.1	12.2 ± 3.6
$\frac{\text{V}^{47} (pn)}{\text{Ti}^{45} (a)}$	17.0 ± 4.03	48.5 ± 7.7	46.9 ± 9.4
$\frac{\text{Sc}^{44} (ap)}{\text{Sc}^{43} (apn)}$	11.8 ± 2.80	35.0 ± 9.2	32.4 ± 10.6
$\frac{\text{V}^{47} (pn)}{\text{Sc}^{43} (apn)}$	10.0 ± 2.40	129.3 ± 33.6	124.6 ± 37.2

^aThe values listed are for an incident energy of 27 Mev.

Fig. 1.2. Isomeric Yield Ratios of Sc⁴⁴ Resulting from the N¹⁴ Bombardment of P³¹, S³², and Cl³⁵.

carried off by the alpha particle, should result in a higher yield of Sc^{44g} from the chlorine reaction than from the S³² and P³¹ reactions. Second, perhaps some reaction mechanism other than compound-nucleus formation is beginning to set in at ~ 18.6 Mev. Such a mechanism could account for the difference found between calculations and experimental results discussed in the previous section.

The ratio is higher for the P³¹ reaction than for the S³² reaction at all energies investigated. Since both reactions bring about the same average angular momentum into the system (seven or eight units), the number of particles emitted from the compound nucleus in the two reactions should account for this difference. The proton emitted in the phosphorus reaction would carry off less angular momentum than the two protons emitted in the sulfur reaction. One should then predict a higher yield of the high-spin isomer in the system left with more angular momentum — in this case the system produced in the P³¹ reaction — which indeed is observed.

Transfer Reactions

The study of transfer reactions in the field of heavy-ion interactions is prompted by the desirability of obtaining information concerning the

nuclear surface. Specifically, these reactions should ultimately result in the reduced widths of the transferring nucleon in the initial and final states.

The following five transfer reactions were investigated: $K^{39}(N^{14},O^{15})Ar^{38}$, $Cl^{35}(N^{14},O^{15})S^{34}$, $Cl^{35}(N^{14},N^{15})Cl^{34m}$, $S^{32}(N^{14},O^{15})P^{31}$, and $Al^{27}(N^{14},O^{15})Mg^{26}$. The excitation functions are displayed in Fig. 1.3.

In addition to predicting the shape of the angular distributions for transfer reactions, Breit and collaborators⁷⁻⁹ derived an expression for the variation of the total cross section with energy. This expression is

$$\sigma = \frac{(\pi\lambda)^2}{2} \left(\frac{1}{\alpha\bar{\alpha}\lambda\lambda'} \right) \times \left[\frac{b_1 b_2}{(1 + \alpha b_1)(1 + \bar{\alpha} b_2)} \right]^2 \exp(x), \quad (1)$$

where

$$x = \frac{\sqrt{2M}}{\hbar} \left[(b_1 + b_2) E_s^{1/2} \left(1 - \frac{E_B}{E} \right) + (\bar{b}_1 + \bar{b}_2) \bar{E}_s^{1/2} \left(1 - \frac{\bar{E}_B}{\bar{E}} \right) \right], \quad (2)$$

b_1, b_2 = radii of initial and final nuclei 1 and 2 respectively,

$\lambda = \hbar/Mv$ = reduced wavelength of the transferred neutron,

v = relative velocity,

E_s = binding energy of the neutron,

$\alpha = (2ME_s/\hbar)^{1/2}$,

M = neutron mass,

$E_B = Z_1 Z_2 e^2 / 1.5(A_1^{1/3} + A_2^{1/3})$ = Coulomb barrier,

E = center-of-mass energy,

⁷G. Breit, *Handbuch der Physik*, ed. by S. Flugge, vol. XLI, pt 1, pp 367-407, Springer-Verlag, Berlin, 1959.

⁸G. Breit, pp 1-15 in *Proceedings of the Second Conference on Reactions Between Complex Nuclei*, ed. by Alexander Zucker, E. C. Halbert, and F. T. Howard, Wiley, New York, 1960.

⁹G. Breit and M. E. Ebel, *Phys. Rev.* **103**, 679 (1956); **104**, 1030 (1956).

Fig. 1.3. Thick-Target Yields Determined for the Investigated Transfer Reactions. For the reaction $Cl^{35}(N^{14},O^{15})S^{34}$, the closed dots show the data obtained with targets containing natural-abundance chlorine; the closed triangles represent the data from targets enriched in Cl^{35} .

and the unbarred and barred quantities refer to the initial and final systems respectively.

In addition to the various kinematical factors, the cross-section expression contains the product of the reduced widths of the neutron in the two participating nuclei $\lambda\lambda'$, where λ refers to the nucleus donating the neutron, and λ' refers to the nucleus which has accepted the transferred neutron. Specifically, for the case $B^{10}(N^{14},N^{13})B^{11}$, λ refers to the neutron-reduced width in N^{14} , while λ' refers to the B^{11} . The probability of finding the neutron in a shell of unit thickness around one of these nuclei is proportional to the reciprocal of the appropriate λ .

To facilitate comparison between theory and experiment, the excitation functions can be plotted as $\log(\sigma/\lambda)$ vs x . In the region where the tunneling theory is applicable ($E < E_B$), it predicts that x should change by a factor of $\ln 10$ for an order of magnitude change in σ/λ^2 .

The available experimental data on single-nucleon transfers¹⁰ have been grouped into three

¹⁰For a complete list of references see K. S. Toth and Eugene Newman, to be published in the *Physical Review*.

sections: (1) N^{14} -induced reactions producing N^{13} as one of the reaction products, (2) F^{19} -induced transfers resulting in F^{18} , and (3) the five reactions investigated during this past year, together with two single-proton transfers studied earlier. These data are plotted in Fig. 1.4. Although the excitation functions, as plotted, obviously do not all have the same slopes, there is a tendency for the heavier-target data to fall on straight lines that group together and have rather similar slopes, close to the value predicted by the tunneling theory. Two targets, B^{10} and N^{14} , behave anomalously in all three sets of data, the anomaly being manifested by a slope that is much more gentle than the one predicted by the tunneling theory and/or by a break in the curves. Another reaction, $Cl^{35}(N^{14}, N^{15})Cl^{34m}$, involving the detection of the isomer of Cl^{34} , also displays a break in the excitation function.

There are four pairs of reactions in which the same target nucleus has been bombarded with both N^{14} and F^{19} beams. The product $\lambda\lambda'$ can be extracted from the value of $\sigma/\mathcal{K}^2$ at the point where

$x = 0$. For the above-mentioned pairs, however, because of the identical targets, four independent values of the ratio $\lambda(N^{14})/\lambda(F^{19})$ can be obtained. Naturally, these four ratios must be identical and serve as a test as to how well the λ 's may be extracted from the curves. In Table 1.2 the reactions, the $\lambda\lambda'$ products, and the $\lambda(N^{14})/\lambda(F^{19})$ ratios are listed. Two entries for the $Al^{27}(N^{14}, N^{13})Al^{28}$ reaction are shown. The values shown are straight-line extrapolations of the data of refs 11 and 12 respectively. The measurements of ref 12 exist only below $x = 0$, whereas those of ref 11 were made at energies above $x = 0$. Of the two $\lambda\lambda'$ products the one deduced from ref 11 yields a ratio, $\lambda(N^{14})/\lambda(F^{19})$, which is closer to those derived from the remaining three pairs of reactions. It must be remarked, however, that both sets of data, refs 11 and 12, involve large experimental errors.

¹¹V. V. Volkov, A. S. Pasiuk, and G. N. Flerov, *Soviet Phys. JETP (English transl.)* **6**, 459 (1958).

¹²W. H. Webb, H. L. Reynolds, and Alexander Zucker, *Phys. Rev.* **102**, 749 (1956).

Fig. 1.4. Single-Nucleon Cross-Section Data Plotted as $\sigma/\mathcal{K}^2$ vs x . $\mathcal{K} = \hbar/Mv$ = the reduced wavelength of the transferred nucleon; x = the quantity shown in the figure. The figure is divided into three portions as follows: at the left (N^{14}, N^{13}) transfers; in the center (F^{19}, F^{18}) transfers; and at the right the present data together with two proton transfers studied earlier. The curves are labeled according to the bombarded target.

Table 1.2. Reduced Widths

Reaction Pair	$\lambda\lambda' \text{ (cm)}^2$	$\lambda(N^{14})/\lambda(F^{19})$
	$\times 10^{-24}$	
$N^{14}(N^{14}, N^{13})N^{15}$	2.20	0.37
$N^{14}(F^{19}, F^{18})N^{15}$	5.98	
$B^{10}(N^{14}, N^{13})B^{11}$	1.61	1.44
$B^{10}(F^{19}, F^{18})B^{11}$	1.12	
$Na^{23}(N^{14}, N^{13})Na^{24}$	4.03	0.88
$Na^{23}(F^{19}, F^{18})Na^{24}$	4.56	
$Al^{27}(N^{14}, N^{13})Al^{28}$	$4.05^a; 12.3^b$	$2.77^a; 8.36^b$
$Al^{27}(F^{19}, F^{18})Al^{28}$	1.46	

^aSee ref 11.^bSee ref 12.

In ref 12 the measured cross section is extremely low, whereas in ref 11 the uncertainty in the N^{14} -beam energy was approximately 10 Mev. Although the agreement among the four sets of ratios is not spectacular, it is gratifyingly close, especially since only kinematical factors and no detailed nuclear structure information were included in the tunneling model.

In an earlier attempt¹³ to systematize transfer excitation functions, the measured cross sections were plotted vs E^* , where $E^* = E_{\text{c.m.}} - E_{\text{barrier}} + Q$. The quantity E^* is the kinetic energy available to the system at the time of contact after the transfer has occurred. Excitation functions plotted in this manner, with a few exceptions, tend to group together. It was hoped that with a few exceptions a "universal curve" existed for transfer reactions and that it could be used to predict unknown cross sections by the calculation of the quantity E^* . Fisher *et al.*,¹⁴ at the suggestion of Breit, re-plotted transfer cross sections vs the expression $E_{\text{c.m.}} - E_{\text{barrier}} + Q/2$. Their "universal curve" brought some excitation functions closer together but displaced others.

The available single-nucleon transfer cross sections at low incident energies were plotted vs

E^* , as shown in Fig. 1.5. Dotted curves represent the five excitation functions obtained in this work, dashed curves show the data of Perkin *et al.*,¹⁵ and the solid curves represent the earlier data obtained with N^{14} beams. Not all excitation functions are shown in the diagram, because some curves overlap and if displayed would tend to be confusing. A sufficient number of curves are shown, however, so that it is readily seen that in fact no "universal curve" exists. Reactions whose E^* values are about -7 or -8 Mev would have been expected, from the earlier "universal curve," to have extremely small cross sections; however, they are shown to possess cross sections of a few millibarns. Also, instead of being closely grouped, the curves are spread over a wide range of E^* . A trend can be observed from Fig. 1.5; that

¹⁵J. L. Perkin, R. F. Coleman, and D. N. Herbert, *Proc. Phys. Soc.* **79**, 1033 (1962).

Fig. 1.5. Single-Nucleon Transfer Cross Sections Plotted as a Function of E^* , where $E^* = E_{\text{c.m.}} - E_{\text{barrier}} + Q$. Dotted curves represent the five investigated reactions; dashed curves show the data of Perkin *et al.*; and the full curves represent earlier data obtained with N^{14} beams. The curves are labeled according to the bombarded target.

¹³M. L. Halbert *et al.*, *Phys. Rev.* **106**, 251 (1957).

¹⁴D. E. Fisher, Alexander Zucker, and A. Gropp, *Phys. Rev.* **113**, 542 (1959).

is, the higher the atomic number of the target, the higher the cross section for a given value of E^* . Plotting the cross sections in the manner of Fisher *et al.*¹⁴ does not bring about any additional clustering around a "universal curve."

TRANSFER-REACTION ANGULAR DISTRIBUTIONS

$\text{Al}^{27}(\text{O}^{16}, \text{N}^{15})\text{Si}^{28}$

The differential cross section of the proton transfer reaction $\text{Al}^{27}(\text{O}^{16}, \text{N}^{15})\text{Si}^{28}$ was measured by using an O^{16} beam of 30 Mev from the ORNL Tandem Van de Graaff. For an assumed radius r_0 of 1.5 fermis, the incident energy is 0.78 Mev below the Coulomb barrier. Two groups of N^{15} particles were observed; these were shown to result from transfers in which (1) both residual nuclei were left in their ground states ($Q = -0.54$ Mev), and (2) N^{15} was left in its ground state and Si^{28} in its first excited (1.78 Mev) ($Q = -2.32$ Mev) state.

The target used was an evaporated, self-supporting aluminum film having a thickness of $125 \mu\text{g}/\text{cm}^2$. The detection system consisted of a scattered particle-recoil particle coincidence apparatus supplemented by a proportional counter to impose a further restriction on the nature of the scattered particle.¹⁶ The proportional counter portion of the scattered-particle identification system described in a previous progress report¹⁷ was replaced by a counter of different design. In the new detector the collector wire is on the axis of the cylinder, and the particles traverse midway between the wire and the wall, parallel to the axis. This arrangement improved the resolution by approximately 5%, thus providing better separation between particles of different nuclear charge.

Figure 1.6 shows the observed angular distributions. It is seen that the ground-ground (G-G) transfer cross section is larger than the G-1st excited-state cross section in the forward direction but smaller on the high-angle side of the peak. Both distributions peak at approximately the same angle and with the same differential cross section.

The integrated cross sections are 1.3 and 1.6 mb for the G-G and G-1st transfers respectively.

The angular distributions were compared with the predictions of the tunneling theory of Breit, bearing in mind that the theory, as formulated, applies to the transfer of neutrons and not protons. To facilitate comparison with the theory and to permit extraction of the interaction radius, the distributions were replotted¹⁷ as $d\sigma/dR_{\min}$ vs $R_{\min}$, shown in Fig. 1.7. The radius parameters, r_0 , of 1.81 ± 0.04 and 1.73 ± 0.04 fermis were deduced for the G-G and G-1st distributions respectively. The solid lines are the predictions of the tunneling theory normalized to the data. It is apparent that the agreement is far better for the G-1st distribution than for the G-G.

Fig. 1.6. Differential Cross Section for the Reaction $\text{Al}^{27}(\text{O}^{16}, \text{N}^{15})\text{Si}^{28}$.

¹⁶Eugene Newman, *Phys. Rev.* **125**, 600 (1962).

¹⁷*Electronuclear Research Div. Ann. Progr. Rept. Jan. 16, 1961, ORNL-3083, p 11.*

Fig. 1.7. Transformed Differential Cross Section for the Reaction $\text{Al}^{27}(\text{O}^{16}, \text{N}^{15})\text{Si}^{28}$. Solid lines are the predictions of the tunneling theory normalized to the experimental data.

Complex-Transfer Distributions

In a recent publication, Kammuri¹⁸ was able to reproduce the angular distribution for complex transfers by a simple semiclassical calculation. These reactions, which involve the transfer of many particles from the projectile to the target, and vice versa, have been observed by Kaufmann and Wolfgang.¹⁹ They are characterized by strong forward peaking and cross sections at incident energy of the order of 10 Mev/nucleon, approaching those of single-nucleon transfers.

Briefly, the approach taken by Kammuri is as follows. It is assumed that these complex transfers occur in the nuclear surface region and that the projectile passes through this region in a Coulomb orbit. With the JWKB approximation, the

classical scattering function $\Theta(l)$ is calculated from a Saxon potential. By obtaining the phase shifts from $\Theta(l) = 2d\eta/dl$ over a narrow region of l , the scattering amplitude is calculated in the usual way; that is,

$$f(\theta) = \frac{1}{2}ik \sum_{l=\Delta}^{l+\Delta} (2l+1)(e^{2i\eta_l} - 1)P_l(\cos \theta),$$

$$\sigma(\theta) = P|f(\theta)|^2.$$

Good agreement with the data is obtained for $l = 76$ and $\Delta = 2$ or $\Delta = 4$, as may be seen in Fig. 1.8.

We have made the same calculation, except that only Coulomb phase shifts were used. The fit to the data for $l = 76$ and $\Delta = 2$ is as acceptable as for the calculations above, as seen by the dashed lines; however, the fit is destroyed for $\Delta = 4$. The interaction radius corresponding to $l = 76$ is 9.8 fermis, or $r_0 = 1.31$ fermis. This means that the

Fig. 1.8. Measured Angular Distribution of F^{18} from the Reaction $\text{O}^{16} + \text{Rh}^{103}$, Along with Various Theoretical Predictions.

¹⁸T. Kammuri, *Proceedings of the International Symposium on Direct Interactions and Nuclear Reaction Mechanisms*, Padua, Italy, 1962, in press.

¹⁹R. Kaufmann and R. Wolfgang, *Phys. Rev.* 121, 206 (1961).

colliding nuclei pass through rather dense regions of nuclear matter and yet retain their elastic orbits, or, in the second calculation, feel principally a Coulomb potential.

ANGULAR-MOMENTUM EFFECTS

On fairly general grounds it is expected that the density of nuclear levels as a function of spin j does not continue to increase as $(2j + 1)$ for large spin, but instead is subject to a strong cutoff. A limitation on the number of levels with high spin in the final nucleus may manifest itself in many ways. Among the most striking are strong forward-backward peaking of the emitted particles and failure of the independence hypothesis for formation and decay of the compound nucleus.

The 28-Mev N^{14} ions accelerated in the ORNL 63-Inch Cyclotron are well suited for studies of the nuclear spin distribution, since they bring in orbital angular momenta typically as high as $l = 12$. The two effects mentioned above were observed in reactions producing alpha particles from bombardment of C^{12} , O^{16} , Na^{23} , and Al^{27} by N^{14} ions. The experimental work is described and some results are presented in ORNL-3257. Additional angular distributions are shown in Figs. 1.9-1.11. Each shows the expected symmetric forward-backward peaking.

The experimental data provide information about the dependence of the residual-nucleus level density on excitation energy and spin. Theoretical expressions for the compound-nucleus cross section to a given final channel have been worked out in a semiclassical approximation by Ericson and Strutinski^{20,21} and quantum mechanically by Douglas and MacDonald.²² In each of these treatments the level density at excitation energy E^* for spin j is assumed to have the form

$$\rho(E^*, j) = \text{const } \rho(E^*) (2j + 1) e^{-j(j+1)/2\sigma^2},$$

where $\rho(E^*)$ is the total density of levels at this energy. The spin cutoff parameter σ is a slowly varying function of E^* . It may be used to define a moment of inertia $\mathcal{J}$ according to

$$\sigma^2 = \mathcal{J}T/b^2,$$

where the nuclear temperature T is given by

$$1/T = d \ln \rho(E^*)/dE^*.$$

²⁰T. Ericson and V. Strutinski, *Nucl. Phys.* **8**, 284 (1958); **9**, 697 (1959).

²¹T. Ericson, *Advan. Phys.* **9**, 425 (1960).

²²A. C. Douglas and N. MacDonald, *Nucl. Phys.* **13**, 382 (1959).

Fig. 1.9. Differential Cross Sections for $O^{16}(N^{14}, \alpha)Al^{26}$ for Various Choices of Al^{26} Excitation Energy E^* at Mean Bombarding Energies of 27.2 and 24.0 Mev.

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Fig. 1.10. Differential Cross Sections for $\text{Na}^{23}(\text{N}^{14}, \alpha)\text{S}^{33}$ at 26.7 Mev Mean Bombarding Energy. Points are missing from some curves at forward angles because alpha particles from carbon impurity in the target obscured the alphas from sodium.

Fig. 1.11. Differential Cross Sections for the Reaction $\text{Al}^{27}(\text{N}^{14}, \alpha)\text{Ar}^{37}$ at 26.6 Mev Mean Bombarding Energy.

In both theories the final result is of the form

$$\frac{d^2 \sigma}{dE^* d\omega} = \sum_{n(\text{even})} C_n P_n(\cos \theta).$$

For comparison with the theory, all the experimental angular distributions were fit with expressions of the above form by the method of least squares. The smooth curves in Figs. 1.9–1.11 are fits for n up to 6.

The semiclassical approximation is valid for reactions with N^{14} . Since it appeared that the approximate theory would be simpler to evaluate than the quantum version, attention was concentrated on calculating the C_n by using the semiclassical theory [Eq. (5.26) of ref 21]. If this were done for a number of choices of σ at a given E^* , comparison with the least-squares fits to the data would then determine the best value of σ for that E^* .

When large angular momenta are involved, even the approximate theory becomes very time-consuming to evaluate for each value of σ ; hand calculations cannot be considered for a thorough

exploration of σ values at each value of E^* for each reaction. Consequently, a FORTRAN program was written for the IBM 7090 to perform these calculations. The program has been used thus far to analyze some of the data obtained with the O^{16} target. The data for the region $E^* = 6$ to 12 Mev in the residual nucleus Al^{26} is consistent with $\sigma = 2.5 \pm 0.5$, which corresponds to $\lambda \approx 0.7 \lambda_{\text{rigid}}$.

Results have also been obtained for the variation of the total level density with excitation energy. Each data point in an energy spectrum was divided by the available phase space and the inverse cross section. Figures 1.12 and 1.13 give examples of these fits for two choices of level density,

$$\rho_1(E^*) = C_1 e^{2\sqrt{a(E^*-B)}},$$

$$\rho_2(E^*) = \frac{C_2 e^{2\sqrt{a(E^*-B)}}}{(E^* - B)^2}.$$

Fig. 1.12. Level-Density Determinations at Two Angles for Al^{26} . Fits to $\rho_1(E^*)$ and $\rho_2(E^*)$ are indicated. The thresholds for reactions in which the observed alpha particle might not have been the first one emitted are shown on the energy scale.

Fig. 1.13. Level-Density Determinations at Two Angles for Ar^{37} .

For the O^{16} target, $B = -1$ gave the best fit; for the others, $B = 0$.

Figures 1.14–1.16 show the apparent values of a at each angle for three of the reactions. The word "apparent" was used to signify that the variation of a with angle does not mean that the level density really changes with angle. Rather, the variation arises because the method of analysis is based on the independence hypothesis, which fails when angular momentum is limited.

The angular-distribution results for the spin cut-off parameter are insensitive to the choice of level-density parameters. For example, doubling the parameter a in the level density $\rho_1(E^*)$ for the alpha-particle channel is equivalent to a reduction of only 15% in $\mathcal{Q}/\mathcal{Q}_{\text{rigid}}$. This insensitivity complements that found for the effect of angular-momentum limitation on the apparent level density, as shown in Figs. 1.14–1.16. That is, although the apparent value of the parameter a is a function

of angle, the variation is relatively small. It is extremely fortunate that the two effects can be separated so clearly; otherwise, it would have been a hopeless task to determine either a or σ from these experiments.

A few comments about the calculations of the theoretical angular distributions follow. For each choice of σ the program for the semiclassical formula calculates all the even-order Legendre coefficients C_n up to some value n_{max} ($n_{\text{max}} \leq 18$) for excitation energies spaced any integral number of Mev apart. Options are included which permit $\mathcal{Q}/\mathcal{Q}_{\text{rigid}}$, instead of σ , to be held constant or to be varied with E^* in a simple way. The energy dependence of $\rho(E^*)$ may also be varied from run to run, if desired; four options are available. The σ and ρ parameters for each of the possible exit channels (maximum number 5) are specified individually. Incident and exit-channel angular momenta up to $29\hbar$ are allowable.

In addition to the C_n , the program also prints out certain intermediate results of physical interest. For example, the total width for compound-nucleus decay and the relative widths for each exit channel

Fig. 1.14. Best-Fit Parameters as a Function of Angle for the Total Level Density $\rho_1(E^*)$ and $\rho_2(E^*)$ for Al^{26} .

Fig. 1.15. Best-Fit Parameters as a Function of Angle for the Total Level Density $\rho_1(E^*)$ and $\rho_2(E^*)$ for S^{33} .

are printed out as a function of the angular momentum l of the compound nucleus.

The program calls for a set of transmission coefficients for all exitchannels at 1-Mev intervals in the channel energy. In the present work these are contained in decks of cards which are punched automatically by the use of a separate program based on the optical-model code of R. H. Bassel and R. M. Drisko of this Division. Well parameters were selected from fits to elastic-scattering data obtained by other investigators.

It seems clear now that the approximate formula is actually more difficult for the computer to evaluate than the exact theory. The former includes spherical Bessel functions of pure imaginary argument which are the classical analogs of certain combinations of Clebsch-Gordan and Racah coefficients. These functions increase without limit for large argument; great care is necessary in programming to avoid severe loss of significant digits and overflow; while at the same time minimizing the computing time. The subprogram finally developed selects downward recursion, upward recursion, or a power-series expansion for the computation, according to the values of the argument and of $n_{\max}$. It is accurate to at least 1 part in 10^6 . Running time of the entire program on

Fig. 1.16. Best-Fit Parameters as a Function of Angle for the Total Level Density $\rho_1(E^*)$ and $\rho_2(E^*)$ for Ar^{37} .

the IBM 7090 for calculations at 11 values of excitation energy is 1.6 min for $n_{\max} = 8$ and 2.4 min for $n_{\max} = 14$.

The quantum-mechanical version is now being programmed, also in FORTRAN. All the Z coefficients needed have already been calculated for angular momenta up to 29 by a code incorporating expanded versions of the Clebsch-Gordan and Racah subroutines of A. Culkowski (Mathematics Division). They are stored on magnetic tape and will be transferred to the computer memory in large blocks when required by the main program. The quantum computation should take far less time than the semiclassical formula.

RESONANCES IN THE $\text{C}^{12}(\text{O}^{16}, \alpha)\text{Mg}^{24}$ REACTION

Recently, attention has been called²³ to resonances in the excitation functions for (p, α) ,^{24,25}

²³U. Facchini, E. Saetta Menichella, and F. Tonolini, *Phys. Letters* **1**, 209 (1962).

²⁴H. Ogata *et al.*, *J. Phys. Soc. Japan* **15**, 1719 (1960).

²⁵G. E. Fischer *et al.*, *Phys. Rev.* **110**, 286 (1958).

(n,α) ,²⁶ (d,α) ,²⁷ and (d,p) ²⁸ reactions in the region $Z = 12$ to 14. The observed structure, approximately 150 keV wide, is prominent even at 25 MeV excitation in the compound system, where levels are expected to overlap and smoothly varying cross sections might have been anticipated. Ericson pointed out²⁹ that such fluctuations are to be expected from the statistical theory of compound-nucleus decay and that under certain conditions they provide a measure of the compound-nucleus lifetime.

To determine whether the structure is restricted to nucleon- and deuteron-induced reactions, we have measured the excitation functions for $C^{12}(O^{16},\alpha)Mg^{24}$ in two energy regions: from 23.9 to 26.0 MeV and from 29.6 to 30.9 MeV excitation in the compound nucleus Si^{28} . Measurements were made at laboratory angles of 30 and 150°, although the former do not cover as large an energy range as the latter. Oxygen-16 ions were accelerated in the ORNL Tandem Van de Graaff accelerator. The energy resolution of the beam, determined by the geometry of the 90° analyzing magnet, was 8 keV.

Alpha-particle groups leaving Mg^{24} in its ground state and first six excited states were identified; the detectors were silicon surface barriers. The variation of center-of-mass angle with bombarding energy amounted to about 0.2°. The second and third excited states differ by only 0.11 MeV and could not be resolved because of the kinematic variation of particle energy over the 3.6° laboratory (5.2° c.m.) angular acceptance of the counter. A better-than-average pulse-height spectrum is shown in Fig. 1.17.

The target was an $11 \pm 3 \mu g/cm^2$ carbon film. The most serious experimental difficulty was the carbon buildup on the target, about $0.6 \mu g cm^{-2} hr^{-1}$. A second silicon counter, fixed at about 62° c.m., detected elastically scattered O^{16} ions and was used to monitor the carbon buildup. The alpha yields were normalized to the elastic scattering. A portion of the target was used until the carbon thickness reached $15 \mu g/cm^2$; the target

was then moved so that the beam hit a fresh part. On the average the target was about 12 to 13 $\mu g/cm^2$ thick, corresponding to an energy loss of about 110 keV for the O^{16} ions, or 48 keV c.m. The latter number is effectively the energy resolution in this experiment. In a later run, a shield at liquid-nitrogen temperature was placed around the target, and no change in target thickness was observed.

Figures 1.18 and 1.19 show the excitation functions for four alpha-particle groups. The yields for the fifth and sixth excited states fluctuated in a similar way; however, the background (probably due to alpha particles from target impurities) made it impossible to obtain reliable measurements of their yields. The cross sections were calculated by comparison with the elastic counting rates, which were assumed to be due to pure Coulomb scattering. To check this assumption, we decreased the beam energy to 17.64 MeV (7.65 MeV c.m.) and measured the elastic counting rate at four angles from 62 to 92°. The rate had a $\csc^4 \theta/2$ dependence and was also larger by a factor of $1/E^2$ at 62° than that for the higher-energy data.

Fig. 1.17. Pulse-Height Spectrum at 20.38 MeV (8.73 MeV c.m.). Alpha-particle groups leaving Mg^{24} in its ground state and first six excited states are indicated. The angular acceptance of the counter was too large to resolve the second and third excited states. The sensitive depth of the surface-barrier detector was adjusted so that no protons or deuterons produced pulses above channel 35.

²⁶L. Colli et al., *Phys. Letters* 1, 120 (1962); 2, 12 (1962).

²⁷C. P. Browne, *Phys. Rev.* 114, 807 (1959).

²⁸J. A. Kuehner, E. Almqvist, and D. A. Bromley, *Nucl. Phys.* 21, 555 (1960).

²⁹T. Ericson, *Advan. Phys.* 9, 425 (1960).

Fig. 1.18. Excitation Functions for Alpha-Particle Groups Leaving Mg^{24} in Its Ground State and First Four Excited States.

In the excitation functions we note first of all that peaks and valleys show up very strongly; evidently, this kind of structure is not restricted to nucleon- and deuteron-induced reactions. The most prominent peaks have widths several times the target thickness; thus the results are not affected appreciably by the experimental resolution. The full width of the peaks at half-maximum varies from ~ 85 to ~ 220 kev.

Rapid variations in cross section imply the participation of long-lived intermediate states. One possible interpretation of these phenomena is based on the statistical model. Ericson has shown²⁹ that according to this model the fluctuations measure the width for decay of the compound nucleus, provided that compound states of similar properties are randomly distributed in energy. If compound states with large matrix elements for transitions to a particular final system are bunched together over a range of energies exceeding the width of any one level, then peaks in the excitation function will be broader than the compound-nucleus width. We conclude that for the narrowest peaks the lifetime of the compound system is no shorter than about 0.7×10^{-20} sec.

Fig. 1.19. Excitation Functions for Alpha-Particle Groups Leaving Mg^{24} in Its Ground State and First Four Excited States.

The data of Ogata *et al.*²⁴ on $\text{Al}^{27}(p,\alpha)\text{Mg}^{24}$ partially overlap ours; the region from 25.1 to 25.6 Mev excitation in Si^{28} (14.1 to 14.5 Mev proton energy) is common to both experiments. The structure in this energy region is less pronounced in the (p,α) data, which may indicate that direct interactions, which can vary only rather slowly with energy, are contributing a large portion of the (p,α) cross section. This supposition is borne out by the data, since the angular distributions²⁴ averaged over this energy region show a backward peak. This is not in conflict with the observation²³ that the angular distributions averaged from 11.0 to 14.5 Mev proton bombarding energy are symmetric about 90° , since the cross sections above 14.1 Mev are small and do not contribute much to the average. The fluctuations in the $\text{O}^{16} + \text{C}^{12}$ experiment appear equally pronounced over the entire energy region investigated; no damping at high energy is observed.

Ericson has suggested that the average compound-nucleus width, Γ , may be determined experimentally by means of the autocorrelation function

$$H(\epsilon) = \frac{\langle [\sigma(E + \epsilon) - \langle \sigma \rangle] [\sigma(E) - \langle \sigma \rangle] \rangle}{\langle \sigma \rangle^2},$$

since this function should include the Lorentz factor $\Gamma^2/(\epsilon^2 + \Gamma^2)$. Figure 1.20 shows the auto-

Fig. 1.20. Correlation Functions for α_0 and α_1 for the 150° Data of Fig. 1.18. The autocorrelations are designated by (α_0, α_0) and (α_1, α_1) ; the symbol (α_0, α_1) identifies the cross correlation.

correlation for α_0 and α_1 for the block of data covering the widest energy range, namely, the 150° data from 23.9 to 26.0 Mev. The width Γ is about 120 kev for each. The significance of the remaining structure in Fig. 1.20 is not clear, particularly the peak near $\epsilon = 9$. For large ϵ the oscillations are probably not significant because the number of data points entering into the calculation of the averages becomes small. Similar autocorrelations have been obtained for $(\alpha_2 + \alpha_3)$ and α_4 ; these are shown in Fig. 1.21.

Figures 1.20 and 1.21 also contain cross correlations between pairs of final states to test Ericson's prediction that different final states are uncorrelated. The cross correlation for states i and j is defined by a symmetrized extension of $H(\epsilon)$:

$$H_{ij}(\epsilon) = \frac{1}{2} \frac{\langle [\sigma_i(E + \epsilon) - \langle \sigma_i \rangle] [\sigma_j(E) - \langle \sigma_j \rangle] \rangle}{\langle \sigma_i \rangle \langle \sigma_j \rangle} + \frac{1}{2} \frac{\langle [\sigma_i(E) - \langle \sigma_i \rangle] [\sigma_j(E + \epsilon) - \langle \sigma_j \rangle] \rangle}{\langle \sigma_i \rangle \langle \sigma_j \rangle}.$$

It may be seen that H_{ij} is satisfyingly small near $\epsilon = 0$ in both Figs. 1.20 and 1.21. The behavior of the cross correlations at large ϵ is not understood, although undoubtedly some of the difficulty arises from the poor statistics alluded to previously.

In any case the remarkable difference between the autocorrelations and cross correlations supports Ericson's picture. The 120-kev width then corresponds to a compound-nucleus lifetime of about 0.5×10^{-20} sec.

Fig. 1.21. Correlation Functions for $(\alpha_2 + \alpha_3)$ and α_4 for the 150° Data of Fig. 1.18.

2. Physics Research with 22-Mev Protons

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The nuclear physics research program at the ORNL 86-Inch Cyclotron continues to be concerned with the structure of nuclei and with nuclear reaction mechanisms. For convenience, this summary is subdivided into five parts, namely, studies of the pickup-reaction mechanism, shell-model studies using pickup reactions, scattering and the optical model, level schemes in highly deformed nuclei, and instrumentation and techniques.

STUDIES OF THE PICKUP-REACTION MECHANISM

The experimental data on (p,d) , (p,t) , and (p,α) reactions obtained with 22-Mev protons show that for each reaction, the cross sections for exciting different final states differ by large factors (10 to 100), even though the reaction Q values may differ by less than 1 Mev, and the angular distributions of the emitted particles are strongly forward-peaked. These attributes of the data are characteristic of direct nuclear reactions, but attempts to pin down precisely the nature of the direct interaction bring one face to face with a knotty problem of the interrelationship between nuclear structure and the reaction mechanism. This problem is of special significance when one attempts to derive nuclear-structure information from intercomparisons of the data from the several reactions.

Formally, the cross section for a pickup reaction may be written as the product of two factors, $\sigma = \sigma_r S$. The σ_r represents the cross section for picking up a nucleon occupying a state of a given binding energy and angular momentum, and S represents the probability that a nucleon will be found in that state.

In an effort to study σ_r for several different kinds of pickup reactions, situations were chosen for which the estimation of S is particularly simple, that is, situations in which S is expected to be unity.

Consider the reaction $Zr^{91}(p,d)Zr^{90}$ leading to the ground state of Zr^{90} . To the accuracy with which Zr^{91} may be considered as Zr^{90} plus one $d_{5/2}$ neutron, $S = 1$ for this reaction. Likewise, insofar as Zr^{92} may be considered as Zr^{90} plus a pair of $d_{5/2}$ neutrons, $S = 1$ for $Zr^{92}(p,t)Zr^{90}$ leading to the ground state of Zr^{90} . Niobium-93 may be considered as Zr^{90} plus a pair of neutrons and a proton. Thus, for the reaction $Nb^{93}(p,\alpha)Zr^{90}$ leading to the ground state of Zr^{90} , S is expected to be unity except for the modification brought about by the fact that the proton is in a different shell from the neutrons.

The experimental data are shown in Fig. 2.1. These data should serve to evaluate the validity of theoretical calculations of the cross sections by the use of distorted-wave methods described in Sec 3.

Similar data have been obtained for (p,d) , (p,t) , and (p,α) leading to Fe^{56} as the final nucleus. It was expected that the approximation that the targets Fe^{57} , Fe^{58} , and Co^{59} look like Fe^{56} plus one neutron, two neutrons, and two neutrons and a proton would not be valid in the same way as it

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Fig. 2.1. Angular Distributions of Deuterons from Zr^{91} , Tritons from Zr^{92} , and Alpha Particles from Nb^{93} Leading to the Ground State of Zr^{90} .

was for the zirconium cases. The interpretation is more complicated due to the presence of partially filled levels in the final nucleus. In the iron case a picture similar to that used to describe the zirconium data can be retained if the Fe^{56} "core" is assumed to be nonspherical. The deformation explains the strong excitation of the $2+$ (0.85 Mev) and $4+$ (2.1 Mev) states in $Fe^{57}(p,d)Fe^{56}$ and the relatively weak excitation of the same states in $Fe^{58}(p,t)Fe^{56}$. The $Co^{59}(p,\alpha)Fe^{56}$ reaction is even more complicated, apparently involving a spherical target and a deformed final state. The data are shown in Figs. 2.2-2.4.

SHELL-MODEL STUDIES USING PICKUP REACTIONS

In the simplest cases of pickup reactions, the interaction between the picked up nucleons and the rest of the nucleus is assumed to be completely described by the shell-model potential. This potential

Fig. 2.2. Angular Distributions of Deuterons, from Bombardment of Fe^{57} with 22.3-Mev Protons, Leading to the Three Lowest States of Fe^{56} .

Fig. 2.3. Angular Distributions of Tritons, from Bombardment of Fe^{58} with 22.3-Mev Protons, Leading to the Three Lowest States of Fe^{56} .

Fig. 2.4. Angular Distributions of Alpha Particles, from Bombardment of Co⁵⁹ with 22.3-Mev Protons, Leading to the Three Lowest States of Fe⁵⁶.

is assumed to be the same for the target and the final nucleus. The difference between the target and the final nucleus is simply that the bound state occupied in the target by the picked up nucleon is vacant in the final nucleus. Thus the pickup of a given nucleon from the target leads to a definite energy level of the final nucleus characterized by the state in which the vacancy has been created.

This picture, oversimplified as it is, works remarkably well near closed shells and is usable with slight modification for a closed shell plus a few nucleons. Consider Nb⁹³(p,d)Nb⁹². The pickup of one of the $d_{5/2}$ neutrons would be expected to leave Nb⁹² in its ground state. The fact that the (p,d) spectra from Nb⁹³(p,d)Nb⁹² and Zr⁹²(p,d)Zr⁹¹ are quite similar indicates that the influence of the odd $g_{9/2}$ proton on the neutron-bound states is small. However, the influence is not unobservable, and there is a wealth of information to be obtained by looking at the $d_{5/2}$ pickup peak with good resolution. As shown in Fig. 2.5, the peak does not consist of a single state but of several states spread over an energy interval of about 450 keV. This is an instance where the simple model works well enough to preserve the

characterization of the neutron-bound state as the $2d_{5/2}$ shell-model level and of the proton-bound state as the $1g_{9/2}$ level. The several observed energy levels in Nb⁹² evidently represent the six possible angular momentum couplings of $g_{9/2}$ and $d_{5/2}$. The exact sequence and spacing are dependent on the force between the proton and neutron and could be used as a means of determining the proton-neutron residual force. The pickup reaction is used to identify those states which can be interpreted as resulting from this type of interaction. The band of states is distinguished by its angular distribution. Within the band the intensities should be proportional to $2l + 1$, where l is the spin of the state. Unfortunately, the six states in Nb⁹² cannot be resolved with the present apparatus; new instruments, described below, will improve the resolution.

Fig. 2.5. Deuteron Spectrum from the Reaction Nb⁹³(p,d)Nb⁹². Note that the $d_{5/2}$ pickup group is broad and shows some structure.

A similar set of states should occur in Zr^{92} for two neutrons in the $d_{5/2}$ shell, except that the Pauli principle excludes three of the six states and only the $0+$, $2+$, and $4+$ states are permissible. These have been studied by the reaction $\text{Zr}^{94}(p,t)\text{Zr}^{92}$. The interaction between two $d_{5/2}$ neutrons is stronger than that between a $d_{5/2}$ neutron and a $g_{9/2}$ proton, and the splitting is sufficient to be resolved. The data led to the following interpretation: The $0+$ state is the ground state, the $2+$ state is at 0.9 Mev, and the $4+$ state is at 1.5 Mev. A similar set of states in Zr^{94} has been found by the reaction $\text{Zr}^{96}(p,t)\text{Zr}^{94}$. The differential cross sections are shown in Fig. 2.6.

In $\text{Zr}^{90}(p,d)\text{Zr}^{89}$ one of the observed states (0.6 Mev) is interpreted as resulting from the pickup of a $p_{1/2}$ neutron (see Fig. 2.7). This state should have the shell-model configuration: two $p_{1/2}$ protons, one $p_{1/2}$ neutron, and ten $g_{9/2}$ neutrons. The ground state of Y^{89} has the configuration: one $p_{1/2}$ proton, two $p_{1/2}$ neutrons, and ten $g_{9/2}$ neutrons. The 0.6-Mev state of Zr^{89} and the ground state of Y^{89} thus have a simple relationship with each other through the substitution of a proton for a neutron. In the reaction $\text{Y}^{89}(p,n)\text{Zr}^{89}$ a

Fig. 2.6. Differential Cross Sections for the Three States Excited by Pickup of a Pair of $d_{5/2}$ Neutrons from Zr^{96} .

Fig. 2.7. Deuteron Spectrum from the Reaction $\text{Zr}^{90}(p,d)\text{Zr}^{89}$. The peak at $Q = -9.8$ is the ground-state group.

state is found which is interpreted as the result of the substitution of a proton for a neutron.⁴ The state found by the (p,n) reaction is at an excitation of 8 Mev. In considering the relationship of the 0.6-Mev state to the 8-Mev state, it is useful to consider isobaric spin. In the reaction $\text{Y}^{89}(p,n)\text{Zr}^{89}$, initially $T_z = 11/2$ and $T = 11/2$, presumably. Since the (p,n) reaction does not change the total isobaric spin, the final state must be $T_z = 9/2$, $T = 11/2$. In the $\text{Zr}^{90}(p,d)\text{Zr}^{89}$ reaction, $T_z = 10/2$ and $T = 10/2$, initially; $T_z = 9/2$, $T = 9/2$, as well as $T_z = 9/2$, $T = 11/2$, is a permissible final state. The $T = 9/2$ state is favored by a factor of 10 in intensity from isobaric-spin considerations alone. It has been suggested⁵ that the energy difference between

⁴J. D. Anderson, C. Wong, and J. W. McClure, *Phys. Rev.* **126**, 2170 (1962).

⁵M. H. Macfarlane, private communication.

the two states represents an isobaric-spin splitting of the type described theoretically.⁶

Nuclear-structure data have been obtained also from $F^{19}(p,t)F^{17}$ and $F^{19}(p,\alpha)O^{16}$. It is interesting to note that $F^{19}(p,t)F^{17}$ excites both the $\frac{5}{2}^+$ ground state and the $\frac{1}{2}^+$ state at 0.5 Mev quite strongly (see Fig. 2.8). This at once indicates that the odd proton in F^{19} cannot be pictured as occupying a definite $j-j$ coupling shell-model state.

Fig. 2.8. Differential Cross Section for Excitation of the Ground State (t_0 Group) and 0.5-Mev State (t_1 Group) in the Reaction $F^{19}(p,t)F^{17}$.

SCATTERING AND THE OPTICAL MODEL

Studies of elastic scattering to explore the dependence of the optical-model well depth on the nuclear-symmetry parameter $(N - Z)/A$ were continued. The new data include scattering of protons from the zirconium isotopes, done at 22.5 Mev with the ORNL 86-Inch Cyclotron, and scattering of protons from the isobar pairs $Ni^{64}-Zn^{64}$ and $Fe^{58}-Ni^{58}$ at 9.6 and 11.7 Mev, done in collaboration with J. Benveniste and A. C. Mitchell on the cyclotron at the Lawrence Radiation Laboratory, Livermore, California.

The data on Zr^{90} , Zr^{91} , Zr^{92} , Zr^{94} , and Zr^{96} , studied over the angular range of 17 to 159°, show

a smooth shift of the positions of the maxima and minima toward smaller angles for the heavier isotopes (see Fig. 2.9). This shift is larger than would be expected simply from the mass dependence and is qualitatively in agreement with an $(N - Z)/A$ dependence of the real potential well depth.

The work on Ni^{64} and Zn^{64} was previously attempted at the ORNL 86-Inch Cyclotron. At 22 Mev an angular shift was not observed. The energy was reduced by degrading with absorbers, but this technique introduced an intolerable energy spread. The experiments were then undertaken at the Livermore variable-energy cyclotron at 9.6 and 11.7 Mev, with good resolution. A shift in the angular positions of the maxima and minima was observed between the two isobars; the Ni^{64} pattern occurred at a slightly smaller angle than the Zn^{64} pattern.

A complication in the interpretation of the $A = 64$ data arises because Zn^{64} has a larger deformation

Fig. 2.9. Elastic Scattering of Protons from Zirconium Isotopes.

⁶J. B. French and M. H. Macfarlane, *Nucl. Phys.* **26**, 168 (1961).

than Ni^{64} ; it is possible that any observed angular shift might be attributed to the difference in deformation rather than to a difference in nuclear-potential well depth. To clarify this point, a second isobaric pair, $\text{Fe}^{58}\text{-Ni}^{58}$, was studied. The Fe^{58} has the larger deformation and the larger $(N - Z)/A$ of the $A = 58$ pair; Ni^{64} has the smaller deformation and the larger $(N - Z)/A$. The angular shift is toward smaller angles for the larger $(N - Z)/A$ in both cases. This is consistent with a dependence of the real potential well depth on $(N - Z)/A$.

This experiment also resulted in the measurement of the excitation energies of 10 levels in Ni^{64} , only 2 of which were previously measured, and of 14 levels in Zn^{64} , some of which were not previously reported.

SYSTEMATIC PROPERTIES OF NUCLEAR LEVELS IN DEFORMED ODD-A NUCLEI

New and more precise data were obtained⁷ from internal-conversion electron spectra for odd- A nuclei in the deformed region $N = 89$ through $N = 113$. The proposed energy levels have been characterized by excitation energy (in kev), spin and parity, and assignments of the asymptotic-limit quantum numbers of the Nilsson wave functions.⁸ The positions and movements of the intrinsic states and the properties of their rotational structures were followed through sequences of odd-neutron nuclei. It was observed that rotational configurations are more unusual at the extreme ends of the deformed region.

The systematic behavior of the parameters which characterize rotational spectra is illustrated in Table 2.1. The last column lists $M1/E2$ mixtures (of photon intensities) for the first rotational excitation in a number of $K = \frac{5}{2}$ bands. The relative $E2$ strengths appear to be a characteristic of the odd-particle orbital, as is observed in the close-lying $\frac{5}{2}^+ [642]$ and $\frac{5}{2}^- [523]$ configurations. It is possible to describe a correlation of experimental moments of inertia with the asymptotic quantum-number assignments. Rotational ($\Delta I = 1$) transi-

tions in cascade are found to have similar $M1/E2$ mixing ratios, in the absence of strong particle-rotational coupling effects.

Certain regularities appear in the properties of the $K = \frac{1}{2}$ band populated in the region between Er^{163} and W^{181} . The $M1/E2$ mixing ratios for rotational transitions between $\frac{3}{2} \rightarrow \frac{1}{2}$ states are low (1.6 ± 0.5) except for the case of Er^{167} , where $M1/E2 = 7$. Figure 2.10 presents the experimental decoupling factor a for the $\frac{1}{2}^- [521]$ configuration. The parameter a corresponds to a partial decoupling of the particle motion from the rotating nucleus. A smooth variation is observed in a as a function of mass number, indicating a maximum of +0.85 for Yb^{171} . Mottelson and Nilsson⁸ have explicitly calculated the decoupling factor as a function of deformation, which is in agreement with experiment. Empirical data for the inertial term, $3\hbar^2/2$, are plotted in Fig. 2.10 to show the relationship between the two rotational parameters.

The trends in the positions of intrinsic energy levels observed in spectra of odd-neutron nuclei may be examined in Table 2.2. Good systematics are observed in the filling of neutron levels according to the sequence of Nilsson orbitals appropriate to prolate-spheroidal deformation. Usually, a level first appears as a high-lying state, decreases in energy with successive neutron numbers until it becomes the ground state (0 kev), then increases in energy again as more neutrons are added.

The energy shift of common single-particle states for successive isotones is, for 20 cases, less than 150 kev and about 60 kev on the average. The remaining 5 cases are distributed about the 200-kev value. The energy spacing between common intrinsic states which appear in neighboring isotopes is found to vary from 20 to 600 kev. The direction of the energy displacement is internally consistent, with a few exceptions. There is, however, greater regularity to the energy shift when a neutron pair is added.

INSTRUMENTATION AND TECHNIQUES

The new 20,000-channel analyzer being constructed by Tullamore Electronics Corporation was tested at the plant with a gamma-gamma correlation experiment by Yale and ORNL personnel. The performance of the analyzer was excellent. Magnetic tapes from the analyzer were processed by

⁷B. Harmatz, T. H. Handley, and J. W. Mihelich, *Phys. Rev.* **128**, 1186 (1962).

⁸B. R. Mottelson and S. G. Nilsson, *Kgl. Danske Videnskab. Selskab, Mat.-Fys. Skrifter* **1**(8), 1-105 (1959).

Table 2.1. Experimental Data for Rotational Bands Assigned as $K = \frac{5}{2}$, Where $E(I_0)$ Is the Energy for the Base State of Spin I_0 , $3\hbar^2/2I$ Is the Inertial Parameter, and $M1/E2$ Ratios Are Obtained from Conversion-Electron L-Subshell Ratios

N	Nucleus	Assigned Orbital $K\pi[Nn_z\Lambda]^a$	$E(I_0)$ (kev)	$3\hbar^2/2I$ (kev)	$I_0 + 1 \rightarrow I_0$ (M1/E2)
89	$^{153}_{64}\text{Gd}$	$\frac{5}{2}^+ [642]$	129.0	46.5	
93	$^{157}_{64}\text{Gd}$	$\frac{5}{2}^+ [642]$	64.0	44.4	34
95	$^{161}_{66}\text{Dy}$	$\frac{5}{2}^+ [642]$	0	37.5	24
95	$^{161}_{66}\text{Dy}$	$\frac{5}{2}^- [523]$	25.6	66.9	0.9
95	$^{163}_{68}\text{Er}$	$\frac{5}{2}^- [523]$	0	72.0	0.12
97	$^{163}_{66}\text{Dy}$	$\frac{5}{2}^- [523]$	0	63	
97	$^{165}_{68}\text{Er}$	$\frac{5}{2}^- [523]$	0	66.2	Pure E2
99	$^{169}_{70}\text{Yb}$	$\frac{5}{2}^- [523]$	570.5	66.8	
99	$^{167}_{68}\text{Er}$	$\frac{5}{2}^- [523]$	585.4	71.5	~ 7
99	$^{169}_{70}\text{Yb}$	$\frac{5}{2}^- [512]$	191.4	75.4	15
101	$^{171}_{70}\text{Yb}$	$\frac{5}{2}^- [512]$	122.4	73.5	
101	$^{173}_{72}\text{Hf}$	$\frac{5}{2}^- [512]$	107.2	77.6	
103	$^{173}_{70}\text{Yb}$	$\frac{5}{2}^- [512]$	0	67.6	20
103	$^{175}_{72}\text{Hf}$	$\frac{5}{2}^- [512]$	0	70.0	17
105	$^{177}_{72}\text{Hf}$	$\frac{5}{2}^- [512]$	508.9	82.6	
107	$^{181}_{74}\text{W}$	$\frac{5}{2}^- [512]$	365.5	94.6	

^aMottelson and Nilsson (ref 8) have used a set of asymptotic quantum numbers $[Nn_z\Lambda]$ and K to characterize the different single-particle states in the limit where the nuclear potential becomes an anisotropic harmonic oscillator.

Fig. 2.10. Empirical Constants for Anomalous Rotational Sequences Based on the $\frac{5}{2}^- [521]$ Configuration.

**Table 2.2. Summary of Intrinsic Excitations (in keV) Listed According to the Nilsson Orbital Description
for Odd-A Nuclei in the Region of Odd Neutron Numbers 89 to 113**

Parentheses are used to designate decreasing reliability of the level assignments; double parentheses designate least certainty

N	Nucleus	$\frac{3}{2}^-$ [532]	$\frac{3}{2}^+$ [402]	$\frac{1}{2}^+$ [660]	$\frac{3}{2}^+$ [651]	$\frac{3}{2}^-$ [521]	$\frac{5}{2}^+$ [642]	$\frac{5}{2}^-$ [523]	$\frac{7}{2}^+$ [633]	$\frac{1}{2}^-$ [521]	$\frac{5}{2}^-$ [512]	$\frac{7}{2}^-$ [514]	$\frac{9}{2}^+$ [624]	$\frac{1}{2}^-$ [510]	$\frac{3}{2}^-$ [512]	$\frac{7}{2}^-$ [503]
89	Sm ¹⁵¹	(344)	((104))	(4)	(0)	((167))	((209))									
89	Gd ¹⁵³	(212)	(109)		(0)	((303))	(129)									
91	Sm ¹⁵³					0										
91	Gd ¹⁵⁵	((326))	((367))	(247)	(86)	0	(105)	((286))								
93	Gd ¹⁵⁷					0	(64)									
95	Gd ¹⁵⁹					0										
95	Dy ¹⁶¹					74	0	25								
95	Er ¹⁶³				((415))	(104)	((22))	(0)		(345)						
97	Dy ¹⁶³						0									
97	Er ¹⁶⁵		((1427))		((853))	(242)	(47)	0	((117))	(297)	(608)					
97	Yb ¹⁶⁷					((239))	(29)	(0)								
99	Dy ¹⁶³								(0)	(108)						
99	Er ¹⁶⁷							((585))	0	207	((347))					
99	Yb ¹⁶⁹							(570)	0	(24)	(191)	(962)				((1465))
101	Yb ¹⁷¹								(95)	0	122	(835)	((936))			
101	Hf ¹⁷³									0	((107))					
103	Yb ¹⁷³								351		0	636				
103	Hf ¹⁷⁵								(207)	125	0	(348)				((1045))
105	Yb ¹⁷⁵										(0)			((455))		
105	Hf ¹⁷⁷								(746)		(508)	0	321			(1058)
105	W ¹⁷⁹										(0)			((221))		
107	Yb ¹⁷⁷											((104))	(0)	((326))		
107	Hf ¹⁷⁹											(215)	0	(375)		
107	W ¹⁸¹							((953))	((746))	365	((408))	0	((385))	((560))	((807))	
107	Os ¹⁸³											0	(170)			
109	W ¹⁸³											((309))	0	208	453	
109	Os ¹⁸⁵												0	127	((356))	
111	W ¹⁸⁵														(0)	
111	Os ¹⁸⁷													0	(74)	
113	Os ¹⁸⁹													36	0	((217))

computers at both Yale and Oak Ridge, and a tape written by the Oak Ridge IBM 7090 was read correctly by the analyzer. The map and contour display were judged to be easy to use and of great value in examining data, both during an experiment and after subsequent processing of the data.

A magnet system for analyzing the external beam of the ORNL 86-Inch Cyclotron and the charged particles from reactions was completed;

an eight-detector scintillation-counter array is nearing completion for use in the focal plane of the magnet. This system will be used for experiments for which the resolution of the dE/dx , E system is inadequate, as, for example, the shell-model studies described above. A lithium-drifted counter was purchased for use as the E counter in the dE/dx , E telescope for data taking. The resolution obtained with it, shown in Fig. 2.7, is in some instances considerably better than that obtained with sodium iodide scintillation detectors.

3. Theoretical Physics

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In theoretical investigations of the mechanisms of nuclear reactions and related nuclear structure information, the elastic scattering of complex particles was analyzed via the optical model. The applicability of the distorted-wave method to stripping reactions was investigated, and for this study a new code was written which allows for a finite range force between neutron and proton. In continuing the study of reactions involving complex particles, the inelastic scattering of carbon ions from carbon was examined.

DEUTERON ELASTIC SCATTERING

The optical-model search program written last year³ was applied in the analysis of 11- to 12-Mev (d, d) data^{4,5} for targets ranging from calcium to tin. Close fits were found in most cases. Figure 3.1 shows some of the best fits obtained. Generally speaking, the fits are not unique; often, two or more discrete sets of parameters, corresponding to distinctly different complex potentials, give good fits to the same data.

For the nuclear part of the optical potential $U(r)$, four different forms were used. These are

described conveniently in terms of the Saxon shape,

$$f_S(r; r_0, a) \equiv \left(1 + \exp \frac{r - r_0 A^{1/3}}{a} \right)^{-1},$$

and the Gaussian shape,

$$f_G(r; r_w, a_w) \equiv \exp - \frac{(r - r_w A^{1/3})^2}{a_w^2}.$$

The four potential forms were:

$$U_{SS}(r) = -V f_S(r; r_0, a) - iW f_S(r; r_0, a),$$

$$U_{SP}(r) = -V f_S(r; r_0, a) - iW f_S(r; r_w, a_w),$$

$$U_{SD}(r) = -V f_S(r; r_0, a) + i a_w \frac{\partial}{\partial r} f_S(r; r_w, a_w),$$

$$U_{SG}(r) = -V f_S(r; r_0, a) - iW f_G(r; r_w, a_w).$$

In most cases the Coulomb potential was assumed to be that between a point-charge deuteron and a uniformly charged sphere of radius $1.3A^{1/3}$ fermis. Results were insensitive to details of the Coulomb assumptions.

The automatic search program used to analyze the data proceeds by the standard least-squares method of Gauss; it minimizes the quantity

$$\chi^2(V, r_0, \dots) = \sum_{\theta} \frac{[\sigma_{\text{theory}}(\theta; V, r_0, \dots) - \sigma_{\text{expt}}(\theta)]^2}{[\Delta\sigma(\theta)]^2}. \quad (1)$$

Here $V, r_0, \dots$ are the adjustable optical-model parameters, and the $\Delta\sigma(\theta)$ are preassigned weighting factors. Each converged solution corresponds

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³R. H. Bassel, R. M. Drisko, and Edith C. Halbert, *Electronuclear Div. Ann. Progr. Rept. Dec. 31, 1961*, ORNL-3257, p 22.

⁴M. Takeda, *J. Phys. Soc. Japan* **15**, 557 (1960).

⁵G. Igo, W. Lorenz, and U. Schmidt-Rohr, *Phys. Rev.* **124**, 832 (1961).

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Fig. 3.1. Good Fits Obtained for Six Different Experimental Cross Sections.

to a *relative* minimum for χ^2 , not necessarily an absolute minimum.

Nine fits to the data for 11.8-Mev deuterons on nickel, as yielded by nine different optical-model potentials, are displayed in Figs. 3.2 and 3.3. The SD fits shown in Fig. 3.2 correspond to two separate χ^2 minima in the six-dimensional parameter space describing SD potentials. Similarly, the five SP fits shown in Figs. 3.2 and 3.3 correspond to five separate χ^2 minima in the six-dimensional SP-parameter space. Potentials intermediate in shape between two such distinct optimum potentials generally yield extremely poor fits (e.g., out of phase with the oscillations of $\sigma_{\text{expt}}/\sigma_R$).

It is apparent from Figs. 3.2 and 3.3 that good fits can be obtained with any of several alternate potential forms. The parameters for the nine fits shown on nickel are listed in Table 3.1; they demonstrate that, even for a specified potential form, good or fair solutions can be found in many different regions of optical-model parameter space.

For most of the 16 experimental cross sections studied, there exist good solutions⁶ related to all four of the nickel solutions shown in Fig. 3.2. The SDa-type fits for all targets are displayed in Figs. 3.4 and 3.5.

Fig. 3.2. Optical-Model Fits Corresponding to Four Different Scattering Potentials. The parameters for these potentials are given in Table 3.1.

Fig. 3.3. Optical-Model Fits Corresponding to Five Different Scattering Potentials. The parameters for these potentials are given in Table 3.1.

Table 3.1 lists parameters for most of the fits shown in Figs. 3.1 to 3.5. Parameters for several other solutions of interest are also included. The quantity ξ^2 , used in Table 3.1 as a numerical index to goodness of fit, is closely related to χ^2 :

$$\xi^2 = \frac{1}{N} \sum_{\theta} \frac{[\sigma_{\text{theory}}(\theta) - \sigma_{\text{expt}}(\theta)]^2}{[0.05 \sigma_{\text{expt}}(\theta)]^2}. \quad (2)$$

⁶A complementary study of these and other data has been made by C. Perey and F. Perey, Neutron Physics Division; they used potentials similar to our SDa and SDb types. Their work emphasizes the variation of V and W with target and bombarding energy, under the condition that the four geometrical parameters have fixed values, the same for all targets and energies.

Table 3.1. Samples of Potentials Yielding Optimum Fits (χ^2 Minima)

E_d (Mev)	Target	Label	V (Mev)	r_0 (fermis)	a (fermis)	W (Mev)	r_W (fermis)	a_W (fermis)	σ_r (mb)	N	ξ^2	$\hat{\xi}^2$
11.15	Ca	SDa	67.5	0.974	1.054	58.3	1.516	0.489	1214	31	6.7	10.4
11.15	Ca ^{(1.1σ)^a}	SDa	67.6	0.978	1.022	56.4	1.518	0.490	1191	31	5.1	8.8
11.15	Ca ^{(1.1σ)^a}	SDc	32.7	0.880	1.233	25.1	1.731	0.639	1452	31	0.82	
11.8	Ti	SDa	49.8	1.183	0.817	48.2	1.434	0.671	1384	74	0.51	0.60
11.8	Fe	SDa	58.4	1.103	0.836	53.3	1.353	0.733	1392	73	0.73	0.75
11.8	Fe ^{(0.9σ)^a}	SDa	57.3	1.105	0.897	55.0	1.375	0.713	1427	74	0.42	0.44
11.8	Ni	SDa	56.4	1.164	0.865	56.6	1.427	0.665	1395	74	0.43	0.45
		SDb	79.5	1.274	0.739	81.6	1.389	0.624	1396	74	0.31	
		SPa	60.5	1.121	0.860	7.59	1.834	0.537	1357	74	0.50	
		SPb	85.1	1.233	0.735	11.25	1.717	0.567	1354	74	0.64	
		SGa	55.9	1.171	0.872	11.51	1.347	1.881	1357	74	0.54	
		SS1	59.1	1.544	0.535	14.7	r_0	a	1358	73	1.2	
		SP1	68.0	1.459	0.451	16.6	1.291	1.134	1543	73	1.5	
		SP2	91.8	1.520	0.502	32.2	1.064	0.289	1346	73	1.4	
		SP3	35.5	1.570	0.524	19.0	1.244	0.368	1298	73	1.6	
11.15	Cu	SDa	64.7	1.065	0.987	57.8	1.457	0.711	1517	31	0.67	0.71
11.8	Cu	SDa	60.6	1.133	0.868	52.7	1.414	0.716	1476	74	0.47	0.47
11.8	Zn	SDa	65.9	1.095	0.824	55.9	1.348	0.774	1460	74	0.53	0.55
11.8	Zr	SDa	63.0	1.1914	0.725	37.4	1.307	0.859	1383	73	0.32	0.36
11.8	Nb	SDa	69.6	1.150	0.697	41.0	1.262	0.810	1214	72	0.35	0.35
11.8	Nb ^{(0.9σ)^a}	SDa	79.9	1.009	0.896	38.8	1.412	0.771	1399	74	0.14	0.33
11.8	Ag ^b	SDaa	56.9	0.967	0.938	52.9	1.276	0.826	1248	68	0.29	
		SDa	90.5	0.940	0.889	65.5	1.229	0.830	1243	68	0.29	0.30
		SDb1	149.5	0.866	0.874	73.9	1.204	0.836	1250	68	0.29	
		SDb2	114.2	1.039	0.791	85.2	1.186	0.817	1240	68	0.29	
11.8	Sn	SDaa	78.3	0.786	1.046	29.9	1.731	0.866	2051	73	1.91	
		SDa	125.7	0.740	1.004	30.9	1.729	0.874	2074	73	1.93	
		SDb	196.9	0.709	0.906	30.1	1.736	0.878	2079	73	1.93	
		SDbb	299.5	0.644	0.922	30.8	1.728	0.883	2083	73	1.95	
11.8	Sn ^c	SDaa	71.5	0.824	1.027	30.3	1.807	0.858	2218	65	0.47	
		SDa	117.3	0.782	0.954	30.7	1.806	0.865	2229	65	0.46	
		SDb	191.7	0.702	0.971	32.0	1.792	0.872	2229	65	0.47	

^aThese results refer to the analysis of renormalized data.^bExperimental points below 31° were ignored for all searches on Ag data.^cExperimental points below 33° were ignored for these searches on Sn data.

Fig. 3.4. Optimized SDa-Type Fits to 11.8-Mev Data.
(See ref 5.)

Here N is the number of experimental points used during search. The index $\hat{\xi}^2$ gives the changed value of ξ^2 when r_0 is fixed at 1.133 fermis, while all other parameters remain adjustable.

Different converged solutions, $\sigma_{\text{theory}}(\theta)$, corresponding to separate χ^2 minima for the same measured cross section, often resemble each other even more closely than they reproduce $\sigma_{\text{expt}}(\theta)$. Compare, for example, the SDb fits shown in Fig. 3.1 with the SDa fits in Fig. 3.3. The similarity also extends to the theoretical reaction cross sections σ_r (see Table 6.1) and to the computed complex phase shifts.

Fig. 3.5. Optimized SDa-Type Fits to 11-Mev Data.
(See ref 5.)

He³ ELASTIC SCATTERING

Data for elastic scattering of He³ from nuclei have been accumulating for the past few years^{7,8} and have been analyzed in terms of the optical model.^{8,9} One remarkable feature of these analyses is the large depths of the imaginary wells used to fit the data, the depths being comparable to or greater than the depth of the real potential. This led to the suggestion that He³ particles are even more strongly absorbed than alpha particles, supposedly because the He³ particle is more easily dissociated by the nuclear medium. Such an interpretation is questionable, because a large imaginary potential gives rise to effects similar to those given by the real potential and also causes absorption. In addition, the optical-model calculations^{8,9} are attempts to provide "best fits" to the measured cross sections, and they show large fluctuations of the parameters as a function of atomic mass.

It is of interest to see if the main features of the measured cross sections can be reproduced by an optical potential whose parameters vary slowly with atomic mass. This property has been demonstrated for nucleons,¹⁰ deuterons,¹¹ and alpha particles.¹²

For these reasons the available He³ data is being reanalyzed. Calculations for the elastic scattering of 29-Mev He³ ions from vanadium, nickel, and copper are shown in Fig. 3.6. It is found that these three cases can be satisfactorily fitted with the same optical potential; the essen-

tial differences are accounted for by the mass and charge differences. The parameters of this well are of the "usual" type, similar to the parameters found in optical-model analyses of the scattering of other particles. If we take the mean free path of the particle in the potential as a measure of absorption, the ratio found for copper from this prediction relative to the previous analysis is 0.3, indicating less absorption. Similar remarks hold for nickel and vanadium. When the reaction cross sections are compared, it is seen that the ORNL calculations show a smooth dependence with mass and are smaller than those previously reported.

Fig. 3.6. Optical-Model Calculations for the Scattering of He³ Ions from Vanadium, Nickel, and Copper, Compared with Experiment.

In the following tabulation, reaction cross sections for He³ scattering from vanadium, nickel, and copper, as computed with the potential shown in Fig. 3.6 and from the calculations of Hodgson *et al.*,¹³ are compared:

Target	$\sigma_R(\text{mb})$	
	ORNL	Hodgson <i>et al.</i>
Vanadium	1381	1521
Nickel	1396	1426
Copper	1439	1739

¹³G. W. Greenlees *et al.*, *Nucl. Phys.* **24**, 334 (1961); P. E. Hodgson, *Nucl. Phys.* **21**, 28 (1960).

⁷D. J. Bredin *et al.*, *Proc. Roy. Soc.* **258**, 202 (1960); G. W. Greenlees and P. C. Rowe, *Nucl. Phys.* **15**, 687 (1960); H. E. Wegner and W. S. Hall, *Bull. Am. Phys. Soc.* **3**, 338 (1958); private communication, 1960; H. E. Wegner and W. S. Hall, *Phys. Rev.* **119**, 1654 (1960); S. Hinds and R. Middleton, *Proc. Phys. Soc.* **75**, 745 (1960); J. R. Priest *et al.*, *Phys. Rev.* **119**, 1295 (1960); G. Parry *et al.*, *Proc. Phys. Soc.* **77**, 230 (1961); D. A. Bromley and E. Almqvist, *Rept. Progr. Phys.* **23**, 544 (1960).

⁸J. Aguilar *et al.*, *Proc. Roy. Soc.* **257**, 13 (1960); J. Aguilar *et al.*, *Nucl. Phys.* **25**, 259 (1961); G. W. Greenlees *et al.*, *Nucl. Phys.* **24**, 334 (1961); H. M. Sen Gupta *et al.*, *Nucl. Phys.* **38**, 361 (1962).

⁹P. E. Hodgson, *Nucl. Phys.* **21**, 28 (1960); **23**, 499 (1961); *Proc. Phys. Soc.* **77**, 997 (1961).

¹⁰F. Bjorklund and S. Fernbach, *Phys. Rev.* **109**, 1295 (1958); F. Perey, to be published.

¹¹E. C. Halbert, to be published; C. Perey and F. Perey, to be published.

¹²G. Igo and R. Thaler, *Phys. Rev.* **106**, 1126 (1957).

ELASTIC AND INELASTIC SCATTERING OF CARBON IONS FROM CARBON

A series of measurements have been made on the Yale Linac to investigate the scattering of 127-Mev carbon ions from carbon.^{14,15} The following effects were observed: angular distributions for elastic scattering, single excitation of one of the carbon nuclei to the 4.43-Mev (2^+) state, and excitation of the 14-Mev (4^+) state.

These data were analyzed in terms of the collective model by assuming that the two-body aspects of the problem are more important than the many-body effects. Calculations have proceeded in two ways: (1) With the reactions treated as perturbations, the elastic scattering was calculated by assuming a spherical well for the optical potential; the results are shown in Fig. 3.7. In this approximation the first term in the aspherical part of the interaction leads to excitation of the first excited state of one of the nuclei.¹⁶ (2) A more exact treatment of the problem leads to a set of coupled equations,¹⁷ which couple the elastic channel to the 2^+ and 4^+ excitations of one of the nuclei; the rotational model is assumed.

The results of these calculations for single excitation of the 2^+ first excited state are shown, along with the measurements, in Fig. 3.8. Two curves are calculations in distorted-wave approximation, with and without Coulomb excitation. The third is the prediction of the strong coupling code, with the same parameters used in the distorted-wave calculation except that the radius parameter is reduced.

The value found for the deformation parameter β is somewhat larger than the value for β found from similar analyses of alpha-particle inelastic scattering or proton inelastic scattering but is within the uncertainty of the Coulomb excitation measurement.

The predictions of the strong coupling code for single excitation of the 4^+ state in carbon are

¹⁴K. H. Wang, S. D. Baker, and J. A. McIntyre, *Phys. Rev.* **127**, 187 (1962).

¹⁵G. Garvey, A. M. Smith, and J. C. Hiebert, to be published.

¹⁶E. Rost and N. Austern, *Phys. Rev.* **120**, 1375 (1960); R. H. Bassel *et al.*, *Phys. Rev.* **128**, 2693 (1962).

¹⁷B. Buck, *Phys. Rev.* **127**, 940 (1962).

Fig. 3.7. Optical-Model Prediction for the Elastic Scattering of 127-Mev Carbon Ions from Carbon.

Fig. 3.8. Predicted and Experimental Cross Sections for the "Single" Excitation of the 4.43-Mev (2^+) State in Carbon by Carbon.

compared with experimental measurements in Fig 3.9. Although details of the angular distribution are not well reproduced, the magnitude is in good agreement with experiment.

Fig. 3.9. Predicted and Experimental Cross Sections for the "Single" Excitation of the 14-Mev (4^+) State in Carbon by Carbon.

FINITE-RANGE CORRECTION TO DISTORTED-WAVE APPROXIMATION

The distorted-wave approximation (DWA) in zero-range approximation for stripping has shown discrepancies with experiment. The use of optical-model wave functions which explain the elastic scattering of deuterons and protons does not improve the situation but, instead, increases the confusion. As shown in the section on elastic scattering of deuterons, there are many potentials which give the same elastic scattering (i.e., asymptotic wave function) but give different predictions for stripping. It was discovered that many of these ambiguities arise from a potential change which allows an additional half wavelength (or multiple thereof) for the lower partial waves, thus changing the character of the wave function in the interior. This has also been shown independently by F. Perey, Neutron Physics Division.

It has been suggested that the contribution from the interior is overestimated by the zero-range approximation, which takes the product of the neutron-proton force and the deuteron internal-wave function as a delta function. A more realistic calculation would take into account the finite range of the neutron-proton force and the extension of the deuteron. Such a modification implies going from a threefold to a sixfold integral.

A DWA code was written which replaces the zero-range approximation,

$$V(r_{np})\phi(r_{np}) = A\delta(r_{np}),$$

by

$$V(r_{np})\phi(r_{np}) = D(r_{np}),$$

where $D(r_{np})$ can be taken as a Gaussian,

$$D(r_{np}) = AN_G e^{-(r_{np})^2 / (R_G)^2},$$

or as the Yukawa form,

$$D(r_{np}) = AN_Y \frac{e^{-|r_{np}|/R_Y}}{|r_{np}|/R_Y}.$$

For flexibility the function which describes the motion of the bound particle relative to the target nucleus is not restricted to a Gaussian but can be taken in any desired form. To conserve computer time and still retain accuracy, the code performs either linear or quadratic interpolation of this function.

Spin-orbit interactions can be included in initial and/or final channels. At present the code is restricted to $l_n \leq 4$ and to 30 partial waves in entrance and exit channels. A comparison of the code with explicit analytic expressions shows agreement within 1.3% over a range of four decades in the angular distribution. Typical IBM 7090 running time is from 4 to 8 min, in comparison with 1 to 2 min for the zero range.

Although the Yukawa form is preferred on theoretical grounds, it was found that if the range R_Y is chosen so that the zero-momentum components agree with the zero-momentum components of the Gaussian function of range R_G , there is essentially no difference between the predicted cross sections. Since the Gaussian function requires substantially less computing time, subsequent studies have been restricted to this form.

A theoretical calculation for 11-Mev deuterons on calcium going to a fictitious state in Ca^{41} with $Q = 0$ is shown in Fig. 3.10. Four curves are shown: the upper set take radial matrix elements from the origin and are labeled ZR (zero range) and FR (finite range); the lower set correspond to taking radial integrals from 4.1 fermis. It is seen that for a small Q the finite-range effects are negligible. In a similar calculation for $Q = 10$ Mev (Fig. 3.11), the finite-range effects are more noticeable but mostly amount to a re-normalization of the calculated cross section. The shape of the angular distribution is little affected; however, the finite-range prediction disagrees with

the zero-range prediction, even with a lower radial cutoff of 4.1 fermis. These calculations and others directly related to experiment tentatively suggest that the finite-range effects, with a reasonable range, do not markedly improve the situation over the zero range. Other effects, such as polarization of the deuteron, nonlocality, and strong coupling, may be important and are being studied.

Several extensions of the code are planned: a study of the heavy-ion nucleon-transfer experiments, where the range of the force is quite large; and a study of the (n,p) reaction, where the use of a zero-range force is wrong in principle.

Fig. 3.10. Comparison of Zero- and Finite-Range Calculation for $\text{Ca}^{40}(d,p)\text{Ca}^{41}$; $l = 1$ with $Q = 0$. The Gaussian range is taken as 1.5 fermis.

Fig. 3.11. Comparison of Zero- and Finite-Range Calculation for $\text{Ca}^{40}(d,p)\text{Ca}^{41}$; $l = 1$ with $Q = 10$ Mev. The Gaussian range is taken as 1.5 fermis.

4. Cyclotron Operations

OPERATION OF THE OAK RIDGE ISOCHRONOUS CYCLOTRON

During the first three months of 1962, efforts were primarily devoted to installing and testing the various components of ORIC. For example, the source and probe mechanism with its vacuum lock, carriage rails, and associated electrical controls was installed, and successful operational checkouts were made. Similarly, the water and vacuum systems with their various interlocks and limit switches were installed and tested.

In the early part of March the operations group started 24-hr coverage five days a week. This coincided with the start of initial test operation of the machine, which included getting operable pressures, providing adequate cooling water to the various components, stabilizing rf excitation, and accelerating a proton beam. The best vacuum obtained about this time was $\sim 1.9 \times 10^{-6}$ torr, with a rate of rise of ~ 0.00045 μ /sec. With the tank under vacuum the temporary rf system was successfully operated at 7.95 Mc/sec with up to 18 kvp on the dee. Details of the testing program are described in Sec 6.

In mid-March the first internal proton beam was obtained at the full radius of 31.5 in. The proton energy was established as 8.0 ± 0.1 Mev through bombardment of stacked copper foils and subsequent counting of the activity and calculations based on range-energy curve and foil thickness. The testing program continued for about three months, during which time numerous internal beam bombardments were made to verify the operational characteristics of ORIC.

Some deflection experiments were made during this testing period. The initial deflection of the internal circulating beam was achieved in the first few weeks of June. A more detailed discussion of this appears in Sec 6.

On July 9, 1962, the testing program on ORIC was terminated to begin installation of the permanent rf system and other associated equipment (electrostatic channel, magnetic channel, and the ion optics) and their supplies, utilities, and controls.

Operational checkout and testing of the permanent rf system was begun in October 1962. This phase of activities continued until, on December 20, 1962, a dee-to-ground potential of ~ 50 kv was obtained. With this initial success, high-energy beams are expected to be available soon in the ORIC.

OPERATION OF THE ORNL 63-INCH CYCLOTRON

As reported earlier, scheduled operation of the 63-Inch Cyclotron was discontinued October 31, 1961. Since then the machine has been kept in standby condition, to be operated occasionally as needed. During the past year, about 30 runs of from 2 min to several hours duration were made for the Heavy-Particle Physics Group. Although these runs were made at widely scattered intervals, the machine operation was reasonably stable and trouble free.

OPERATION OF THE ORNL 86-INCH CYCLOTRON

The responsibility for operation of the 86-Inch Cyclotron was assumed by the Isotopes Division on December 1, 1961. Since then the Proton Physics Group has continued to use the machine for about 36 scheduled hours per week. The Isotopes Division is paid the current hourly rate for use of the machine.

5. Accelerator Development

E. E. Gross	M. B. Marshall	W. R. Smith
E. D. Hudson	J. A. Martin	W. H. White, Jr. ³
R. J. Jones	C. E. Murphy ¹	R. E. Worsham
R. S. Livingston	T. E. Northup ¹	N. F. Ziegler
R. S. Lord	E. G. Richardson	A. Zucker
J. E. Mann	F. M. Russell ²	

A number of major advances in accelerator development and technology were made during the year. Experimental studies on the eight-sector electron model, Analogue II, led to very successful deflection of the beam in November 1962. Although the investigations are still incomplete, the results obtained have removed one of the major uncertainties associated with the proposed Mc^2 cyclotron. This uncertainty centered around the radioactivity problem resulting from the residual undeflected beam being dumped onto the structure of the cyclotron. Estimates of the radiation levels that would be encountered had varied widely; they can now be narrowed to much more reliable calculations. These new estimates were incomplete at the close of the year and will be described in subsequent reports.

An innovation in cyclotron design, designated the Separated Orbit Cyclotron (SOC) and sometimes called the "beehive" or "helitron," was conceived, and a preliminary report was prepared. The significance of this new device is difficult to assess accurately at this early stage, but it is believed that with additional development the machine may emerge as an important new type of accelerator for the $\frac{1}{2}$ - to 10-Bev energy range.

The Laboratory made a presentation of its plans and projected experimental program for the Mc^2

cyclotron to the Ramsey Panel.⁴ It is expected that the report of the panel will become available during the spring or summer of 1963. These plans and other details of the project are also summarized in a status report⁵ issued in June 1962.

A special conference was held at Gatlinburg, Tenn., November 12-13, 1962, on the general subject of "Research in Physics Below One Bev." A summary report of this conference will appear in the March 1963 issue of *Physics Today*. The general consensus of the delegates was that a rich and important program of research awaits the high-intensity "meson factories."

CYCLOTRON ANALOGUE II

Successful operation of the eight-sector electron cyclotron was reported last year. This machine models the particle dynamics expected in the 810-Mev Mc^2 proton cyclotron under study at ORNL. The Analogue is being used to verify the main features of the design and performance of that machine. In recent tests a beam-deflection efficiency of 85% was obtained. This high deflection efficiency will considerably ease the problem of keeping the activation of internal components of the large proton cyclotron within manageable limits.

¹Engineering and Mechanical Division.

²On leave from Rutherford Laboratory, Harwell.

³Instrumentation and Controls Division.

⁴Special panel to the GAC-PSAC to recommend levels and directions for future high-energy accelerator projects.

⁵The Mc^2 Isochronous Cyclotron, ORNL-3324 (June 15, 1962).

The Analogue uses an eight-sector moderate-spiral magnetic-field configuration produced entirely by air-cored windings to produce the field distribution shown in Fig. 5.1. Several advantages accrued from the choice of an iron-free system, chief among which was the ability to produce a highly precise magnetic field with well-known focusing properties without recourse to a lengthy field measurement and correction program.

The central magnetic field in the Analogue is approximately 41.9 gauss; the orbit frequency is 117 Mc/sec. The cyclotron unit, c/ω , is 16.00 in. The maximum energy which can be achieved (limited by loss of axial focusing) is approximately 530 kev. The energy of the extracted beam, at a mean radius of 13.4 in., is about 445 kev.

During the initial operation of the Analogue, a major fraction of the beam was lost at a radius of 10.4 in.; also, an axial oscillation of the beam

envelope was noted at 12.6 in. The trouble at 10.4 in. was at first thought to be caused by either the $\nu_r = \frac{4}{3}$ or $\frac{8}{6}$ resonance, but it was later shown to be the difference-coupling resonance $\nu_r - \nu_z = 1$. When the horizontal component of the geomagnetic field was canceled, this attenuation was eliminated. The disturbance at 12.6 in. was thought to be the sum-coupling resonance $\nu_r + \nu_z = 2$, and this was verified as described later.

To identify the resonances uniquely, advantage was made of the fact that large changes in the axial focusing frequency can be produced by small changes in the amplitude of the azimuthal variation in the magnetic field; the radial focusing frequency is practically unaffected. The azimuthal variation was modified by changing the sector-coil current. The cyclotron was operated at 97, 98.5, 100, 102.5, and 105% of the standard sector-coil current settings. Each setting required a different set of currents for the 5 main circular coils and

Fig. 5.1. Contour Map of One Quadrant of Eight-Sector Field of Analogue Magnet, in Gauss.

the 32 trimming coils. These currents were derived by least-squares fitting to provide an isochronous mean magnetic field in each case. For the several conditions of operation, the locations of the resonances were recorded. These are indicated in Fig. 5.2 by bars which extend from the point where the attenuation or axial motion began to the point where the effect ceased. The solid lines are the computed equilibrium orbit properties for the several currents. The results show clearly that the movement of the inner and outer resonances is in accordance with $\nu_r - \nu_z = 1$ and $\nu_r + \nu_z = 2$ respectively.

Attenuation

A typical curve of the electron current as a function of radius, shown in Fig. 5.3, illustrates the severe attenuation that occurs at the difference-coupling resonance if the horizontal component of the earth's magnetic field is not compensated. This particular curve was taken with an electron source without an accelerating electrode, or slits, to collimate the beam.

The decrease in beam current beyond a radius of 10 in. has been the subject of much study. Gas scattering, lack of isochronism, and loss at reso-

nances have been largely eliminated as causes. The most likely explanation appears to be the electron scattering from the tip of the probe, which results from the small radial width of the beam relative to the effective range of the electrons. At the 10-in. (150-kev) radius the range of the electrons in the aluminum probe is about 0.1 mm and the radial width of the beam is about 0.3 mm. At 450 kev the radial width decreases to 0.1 mm and the range increases to about 0.55 mm. At this much greater ratio of range to radial width, the probability of electrons leaving the probe tip after scattering through small angles is greatly enhanced.

Some preliminary tests of this hypothesis were made by using probe tips of different materials. Attenuation curves taken with aluminum and tantalum probes under identical cyclotron operating conditions are given in Fig. 5.4. At low energies the tantalum shows much lower readings, in agreement with published back-scattering ratios, but at the highest energies the relative decrease is much lower. This is because the maximum range of electrons in tantalum is less than that in aluminum by a factor of 6. The ratio of beam width to range for tantalum is 1 rather than 5.5 for aluminum; hence the fractional loss by small-angle scattering is much reduced.

Fig. 5.2. Correlation of the Location of the Sum- and Difference-Coupling Resonances with Sector-Coil Current.

Fig. 5.3. Typical Attenuation Curves, Showing the Effect of the Difference-Coupling Resonance.

Fig. 5.4. Attenuation Curves Taken with Aluminum and Tantalum Probes.

The dips in beam current that occur at outer radii are located at points where the radial betatron frequency ν_r has the values $\frac{3}{2}$, $\frac{5}{3}$, $\frac{7}{4}$, and $\frac{9}{5}$. The decrease in current results from narrowing of a portion of the beam on the probe tip. At these values of ν_r , a node in the betatron oscillation about the equilibrium orbit recurs after an

integral number of revolutions; for example, at $\nu_r = \frac{3}{2}$, three complete oscillations occur in precisely two revolutions.

Injection of Electrons

The observations and measurements previously reported were obtained with a fixed filament mounted at the center of the cyclotron. In a later version the filament could be moved radially between the excited dee and the dummy dee to optimize its location for a given dee voltage. An attempt to improve the performance of this later system by the addition of an accelerating slit mounted on the lip of the excited dee was only moderately successful, chiefly because the accelerating slit was fixed and the system was difficult to optimize. Finally, an electron source was evolved which injects a highly collimated beam at an energy of 3.3 kev.

The electron injector, shown schematically in Fig. 5.5, is a two-stage device; the first stage defines the beam, and the second adjusts the energy. This arrangement has the advantage of minimizing the size of the device without unduly sacrificing performance. Electrons from a heated filament are accelerated by a potential of about 600 v through the first slit, which has an aperture of 4 mm axially by 1 mm radially. They then pass

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Fig. 5.5. Electron Injector.

through a 180° spectrometer to an image slit of the same dimensions. At 90° a 1-mm slit defines the angular acceptance. As the electrons emerge from the image slit, they are accelerated through an additional 2700 v so that their final energy is 3300 ev, which corresponds to an orbit radius of 45 mm in the central field of the Analogue. The assembly pivots about the exit slit so that the angle of injection may be adjusted.

Certain features of the performance of the Analogue are much improved by the injection of the highly defined beam. It is now possible to accelerate the beam through the difference-coupling resonance $\nu_r - \nu_z = 1$ without attenuation, even without the horizontal magnetic field compensated; also, the beam accelerates through $\nu_r = 2$, with only slight evidence of radial blowup. Finally, the results of the extraction studies which follow show that the radial amplitudes must be small enough to be practically unaffected by the $\frac{8}{4}$ resonance in the absence of the $\cos 2\theta$ bump field. With the $\cos 2\theta$ bump field the radial amplitude grows at two opposing hills only, which would not be the case if the beam entered the resonance region with large incoherent radial oscillation.

Beam Extraction

The beam-extraction system for the Analogue duplicates in principle the method proposed for the Mc^2 cyclotron. The gain in radius per revolution of the particles at extraction radius is too

small to permit entering of a magnetic or an electric channel, about 0.003 in./turn in the Analogue and about 0.050 in. for the Mc^2 cyclotron. An additional mechanism is necessary to increase the turn separation at the extraction radius. The method used is based on the properties of the $\frac{8}{4}$ resonance ($\nu_r = 2$) which occurs at 445 kev in the Analogue and at about 810 Mev in the Mc^2 cyclotron. It has been shown⁶ that at the $\frac{8}{4}$ resonance the change in radius per revolution is proportional to the cube of the amplitude; that is, $dr/dn = C(r - r_0)^3$. The value of the constant C is about 200, so that for very small amplitudes, for example, $(r - r_0) = 10^{-3}$, dr/dn is only 2×10^{-7} cyclotron unit/turn. This illustrates the small-amplitude stability of the resonance. To make the resonance useful for beam extraction, a small $\cos 2\theta$ component is added to the magnetic field to destroy the small-amplitude stability by driving the $\frac{2}{1}$ resonance.

The gain in amplitude per turn in the $\frac{2}{1}$ resonance is independent of initial amplitude, and the effect is sufficiently strong that only a few tenths percent of second harmonic relative to the mean field is required to develop enough amplitude so that the nonlinear resonance can increase the turn separation rapidly.

The maximum amplitude growth occurs at the hills in the magnetic field. This is illustrated by Fig. 5.6, which is a plot of the path of a particle on the sixth and seventh revolutions after an initial displacement of 0.01 cyclotron unit from the equilibrium orbit. The equilibrium orbits for 445 and 550 kev are also plotted for reference.

After the turn separation of the beam has been amplified by the combination of the $\cos 2\theta$ field perturbation and the nonlinear resonance, an additional mechanism must be provided to permit the particles to leave the cyclotron. The magnetic field must decrease sharply (in a magnetic channel), or an electric force must be provided to counteract that of the existing magnetic field. In the Analogue an electrostatic channel is used.

The Analogue extraction mechanism, Fig. 5.7, consists of two 0.005-in.-thick tantalum strips separated by a distance of about $\frac{1}{8}$ in. The inner of these (the septum) is grounded, whereas the outer (the deflector) is insulated so that several

⁶M. M. Gordon, "Sector-Focused Cyclotrons," p 234 in National Academy of Sciences - National Research Council Publication 656, 1959.

Fig. 5.6. Typical Particle Paths in the 8/4 Resonance.

Fig. 5.7. Extraction Mechanism for Analogue Beam. Pencil indicates the exit.

kilovolts may be applied. The channel is supported at five equidistant points, each of which can be moved radially by means of a screw adjustment to make the position of the channel match that required by the beam trajectory. An additional screw permits precise adjustment of the entrance angle of the channel without changing the entrance position.

Azimuthal positioning of the electrostatic channel assembly is by a rack-and-pinion mechanism. Movement of the several adjusting screws from outside the vacuum chamber is done with a multi-headed screwdriver operated by a sealed shaft through a ball-and-socket vacuum seal on the faceplate.

The $\cos 2\theta$ magnetic-field perturbation is provided by coils wound symmetrically to produce two hills and two valleys in the magnetic field without any effect on the average field. The coils are attached to the top and bottom lids of the vacuum chamber and are movable in azimuth to optimize the phase of the field perturbation.

To date the best extraction efficiency obtained has been about 85%, with an extractor voltage of about 1.9 kv. This is a gradient of about 6 kv/cm. The optimum $\cos 2\theta$ amplitude is about 0.3% of the mean field. The beam impinging on a phosphor-coated target at the exit of the extraction system, Fig. 5.8, produces a spot approximately 1×5 mm. This electric field (6 kv/cm) in the Analogue is equivalent to a magnetic channel strength of 3000 gauss for the Mc^2 cyclotron.

The entrance of the extractor is about 8° forward of the hill (see Fig. 5.6). To characterize the dependence of extraction efficiency on septum thickness for the present azimuthal location of the entrance, the septum thickness was increased stepwise by attaching metal-foil strips and measuring the extraction efficiency after each addition. The results, Fig. 5.9, illustrate several interesting features. First, the roughly linear relation between entrance thickness and extraction efficiency shows that the radial distribution of the beam entering the channel is approximately uni-

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Fig. 5.8. Extracted Beam on a Phosphor-Coated Target. Actual size of the beam spot is 1×4 mm.

Fig. 5.9. Dependence of Extraction Efficiency on Septum Thickness.

form. Second, the efficiency does not extrapolate to 100% at zero entrance thickness, which suggests that the septum is improperly shaped at the entrance or that the entrance is effectively thicker because of the inherent angular distribution in the beam. Third, the efficiency extrapolates to zero at about one-half the channel aperture; therefore the beam does not fill the channel at the entrance. This is in agreement with Fig. 5.6. If we assume that the channel is filled at the point of maximum turn separation as a result of optimizing its shape, gradient, and the bump amplitude, then the beam width would be approximately a factor of 2 less at the channel entrance. It may be that higher efficiencies can be realized by moving the entrance of the channel nearer the point of maximum turn separation. Further experimental work, coupled with computer studies, will undoubtedly lead to a better understanding of the situation.

THE Mc^2 CYCLOTRON FACILITY

Detailed investigations of many phases of the Mc^2 Cyclotron Facility are being made in preparation for a final evaluation of its cost and feasibility. The status of these studies was described in a comprehensive special report.⁷ In the subse-

⁷The Mc^2 Isochronous Cyclotron, ORNL-3324 (June 15, 1962).

quent paragraphs the status at the close of this year is reviewed for the cyclotron design, building design, site consideration, magnet studies, rf cavity studies, and beam facilities design.

Other problems under intensive investigation but with results too incomplete to warrant reporting at this time are (1) an accurate estimate of the residual radioactivity associated with the cyclotron, (2) an improved design for the beam optics system for the experimental areas, (3) detailed plans for fabrication and assembly of the components of the machine, (4) the structurally sound design for the building to house the facility and staff, and (5) a detailed cost estimate for the whole project.

Conceptual Design

The Mc^2 Cyclotron. — Since the last progress report, preliminary specifications for the cyclotron have been established (Table 5.1). These specifications will be revised as indicated by the magnet and rf-cavity studies now in progress. The arrangement of the eight spiraled magnet sectors with the coaxial rf cavities, as presented in the previous report, is shown in Figs. 5.10 and 5.11. Systems for the installation, support, removal, and servicing of the magnet and rf cavity are under study.

The magnet support structure uses large columns with interconnected ring girders for rigidity. The columns penetrate the lower vacuum head and terminate on suitable foundations. An alignment system for individual sectors will be provided at the magnet support point in the chamber. A 150-ton overhead bridge crane will be used to assemble and service the machine. Owing to the large orbit separation at the center of the machine, stanchions can be used to space the magnet gap near the center and to prevent the large deflections of the sectors which would result from magnetic forces. When fully assembled, the overall height of the magnet yoke will be about 14 ft.

Because of the critical requirements on magnet alignment and the need for simplicity of construction, it now appears that the vacuum-tank system shown in Figs. 5.10 and 5.11 will best meet the requirements. With this system, both vertical and horizontal loadings due to atmospheric pressure are removed from the magnet. Since the vacuum-chamber head is removable, the installation, alignment, and maintenance of the cyclotron components

Table 5.1. Preliminary Design Specifications
for the Mc^2 Cyclotron

Proton energy, max (internal beam)	900 Mev
Proton energy, extracted beam	810 Mev
Mean orbit radius, extracted beam	230 in.
Number of sectors	8
Spiral of sectors	$\theta = (\pi\omega/c)^2$
Tan γ , at extraction	1.41
Central magnetic field	4500 gauss
Maximum magnetic field	18,000 gauss
Orbit frequency	6.86 Mc/sec
Beam space	4 in.
Magnet gap	8 in.
Magnet power	10.0 Mw
Magnet weight, steel	4800 tons
Magnet weight, copper	120 tons
Accelerating system	2 cavities, 4 gaps
Radio-frequency ^a	13.72 or 20.58 Mc/sec
Energy gain, max	1 Mev/turn
Radio-frequency power	500 to 800 kw
Extraction system	$\cos 2\theta$ magnetic bump at $r_r = 2$, with magnetic channel
Extracted current	100 μa
Vacuum volume	2.6×10^6 liters

^aSeveral cavity systems are being evaluated; they will operate on either the 2d or the 3d harmonic of the orbit frequency, depending on the system chosen.

are greatly facilitated. The vacuum tank will be 60 ft in diameter and 50 ft high. Preliminary investigation shows that, by using 30-in. T-beams for ring girders and 6-in. vertical T-beams spaced 3° apart, the tank wall can be fabricated from 0.5-in. plate stock. The dished heads will have a thickness of 0.5 in. except near the periphery, where they will be 0.75 in.

The design of the vacuum system is based on the desired operating pressure and the expected gas load. The operating pressure selected is 1×10^{-6} torr. The gas load is determined by leaks, which can be minimized, and by outgassing, which is proportional to the total surface area and depends on the type of material exposed to the vacuum. Reasonably accurate estimates of the surface areas and types of materials can be

made, but the wide variation in the published outgassing data makes it difficult to estimate with confidence the pumping speed required.

The previous estimate (last progress report) that 32 five-stage 32-in. diffusion pumps would be required was based on published outgassing data. The approach now being used is to determine the outgassing and surface areas of ORIC and then extrapolate to determine the pumping speed needed for the Mc^2 cyclotron. These test data indicate that approximately 20 five-stage 32-in. diffusion pumps will be required to produce a pressure of 1×10^{-6} torr in 10 hr.

The forevacuum system under study consists of three blowers in series-parallel arrangement, backed by three oil-sealed mechanical pumps. This system will evacuate the tank to 0.05 torr in about 1 hr and 40 min; the blower system would then be used to back the diffusion pumps. The speed of this backing system is sufficient to maintain a pressure of 0.1 torr at the outlet of the diffusion pumps while they are operating at maximum throughput.

Additional data will be taken from the ORIC vacuum system, and efforts will be continued to determine the most reliable outgassing data. As probable radiation intensities are determined, materials of construction and servicing methods will be studied. The many vacuum seals will require very careful consideration. Elastomer seals are preferred where possible. Undoubtedly, all-metal sealing techniques will prove practical for some applications.

The Mc^2 Building. — Studies of the building requirements for the Mc^2 facility led to the development of the conceptual design shown in Figs. 5.12 to 5.15. The key to the design is the large shielded area. The arrangement of this area is based on the planned physics program, with careful consideration for maximum versatility and possible future experiments.

The shielded area contains the cyclotron, the beam corridor, and three large experiment rooms. The cyclotron is housed in a large vault at one end of the building. Access to the cyclotron for installation and servicing is through removable roof blocks or through a 6-ft-wide personnel maze. A 150-ton overhead bridge crane is provided for moving roof plugs and heavy machine components. Space in the cyclotron building is also provided for shops, utilities, and assembly or staging areas.

Fig. 5.10. Plan View and Section of the Mc^2 Cyclotron.

On the ground floor the three large experiment rooms and the beam corridor may be entered through large rolling-plug doors. These doors are large enough to permit passage of trucks for delivery or removal of equipment. Overhead bridge cranes in each room would be used for installation and servicing of experimental equipment. Considerable versatility in the arrangement of experiments is provided by full-length 6-ft-high slots (to be filled with removable blocks) in the walls between the beam corridor, the cyclotron, and the experiment rooms.

The mazes for personnel access to the experiment areas also serve as auxiliary utilities tunnels. Most of the shield penetrations for utilities will be cast into the concrete floor and shielding walls, thus leaving space in the mazes for any additional utilities that may be needed later.

Some changes may be required in the general layout of the shielded areas as a result of continuing studies of the ion-optics system. Also, structural design requirements relating to the large foundation loads may suggest certain changes in the layout.

Very thick shielding is required because of the intense proton beam capability of this cyclotron. This shielding represents a considerable part of the facility cost and therefore warrants very careful study. Preliminary studies indicate that, by using compacted, crushed limestone and earth in appropriate places, considerable savings can be effected. This feature will be studied further in conjunction with the structural studies presently under way.

The results of a study of four possible roof designs for the 80-ft-wide experiment rooms indicate that an arched roof with an earth cover

Fig. 5.11. Vertical Section of the Mc^2 Cyclotron.

Fig. 5.12. Mc^2 Cyclotron Facility.

Fig. 5.13. Ground-Floor Level of Mc² Cyclotron Facility.

would be the most economical. The controlling cost factor in Fig. 5.16a is the quantity of concrete, and in Fig. 5.16b it is the reinforcing steel that would be required. The design shown in Fig. 5.16c is lower in cost but is not as economical as that in Fig. 5.16d, which places the concrete in compression and, therefore, greatly reduces the amount of concrete and steel.

The office and laboratory building is placed adjacent to the experiment areas to provide a central headquarters for research and operating personnel. The building will be of conventional construction and will have three floors. On the ground floor, space is assigned for utilities, storage, and for the three plug doors in the open position. The second floor contains, in addition to office and laboratories, the cyclotron control center and counting room. This location provides for the shortest possible length of instrument and

control wiring. The upper floor contains offices and laboratories.

A study of the structural problem of this building design is under way. This study has not progressed to the point that results can be reported at present. Problem areas appear to be the very high retaining walls, the large foundation loads, and the horizontal thrust of the arched roofs.

The Mc² Site. — A tentative site has been selected for the facility. It is about 1500 ft east of the main laboratory area and directly south of Building 6000 (see Fig. 5.17). This site is close to an existing road; therefore only a short approach road need be constructed. It provides a reasonably flat area about 2000 ft long and 100 ft wide (see Fig. 5.18). This area is parallel to a large hill and is of sufficient elevation to be well above the existing water table and to provide excellent drainage. The cyclotron is arranged so

Fig. 5.14. First-Floor Level of Mc^2 Cyclotron Facility.

that the proton beam is directed east, away from the Laboratory. An open area extending about 1000 ft beyond the end of the beam corridor is available for future expansion or experiments. Bus transportation to the main laboratory on an existing bus route will be convenient for the use of the existing facilities.

On the site selected, incomplete geological information indicates a limestone formation about 20 ft below the surface. Core drillings will be made and evaluated to determine the underground rock structure in detail before a final site selection is made.

Development Studies

The two basic design requirements of the Mc^2 cyclotron are (1) a method for producing a magnetic field of suitable focusing and isochronous

properties and (2) a radio-frequency system with the appropriate frequency and with the desired electric gradient to accelerate the ions. Also, the design of the experimental facilities associated with the cyclotron depends basically on an ion-optics system for delivering beams of specified energy definition, purity, and intensity to locations where experiments can be performed. Some details of these basic studies are described below.

Magnet Studies. — The initial study of the magnetic-field requirements for the Mc^2 cyclotron was concerned with developing a system that could generate the desired magnetic-field characteristics. At that time, relatively little consideration was given to minimizing power and steel requirements. This initial study led to a design that was incorporated in a 0.15-scale model consisting of three of the eight sectors. Field measurements

Fig. 5.15. Second-Floor Level of Mc^2 Cyclotron Facility.

on the model verified that the magnetic-field configuration desired for the Mc^2 can be readily generated in an iron-core magnet. In the model the field vs azimuth closely approximates a trapezoid (see Fig. 5.19), very much as was expected in the initial study.

The calculated and measured peak (hill) field vs radius, shown in Fig. 5.20, agree well within the accuracy of the measurements. The measured and calculated average fields vs radius are in equally good agreement (see Fig. 5.21). The measured and calculated flutter vs radius, Fig. 5.22, also have remarkable agreement at radii larger than 0.5 of maximum radius. At smaller radii the flutter in the model is about a factor of 2 larger than desired, because of the difficulty in accurately calculating the field in this region. Actually, the difference between the calculated and measured field shape is not very large. For

example, at a 15-in. model radius the flutter can be reduced to the desired value by widening the hill about 5° and reducing the hill field a few percent to maintain the desired average field.

These data obtained with the model clearly demonstrate that this design is feasible for the Mc^2 cyclotron if construction of the full-scale magnet directly follows the model coil construction; however, the power requirement would be about 16.5 Mw. By eliminating the extra leads, required on the model to obtain the desired ampere-turn distribution, and by more efficient use of the available volume for conductors, it is estimated that the power requirement for the large magnet can be held under 8 or 10 Mw. Some additional reduction in power may result from widening the gap between pole faces to allow more space for copper. This method of optimizing the design is under study.

(a) CAST CONCRETE

(b) CAST CONCRETE, WITH EARTH FILL

(c) PRECAST CONCRETE, WITH EARTH FILL

(d) CAST CONCRETE ARCH, WITH EARTH FILL

Fig. 5.16. Shielding Studies.

After the initial measurements were made on the 0.15-scale model, the experimental program was directed toward investigating alternate designs for attaining the desired magnetic field. In one method studied, the gap was varied to produce the desired radial gradient; in another, the cross section of the yoke or pole was varied to utilize the saturation of the steel to produce the desired radial gradient. Considerable preliminary data were collected on these methods, and reasonable radial gradients were obtained. Radial gradients of over 1.3 kilogauss/in. (full scale) were obtained by sloping the pole-face surfaces in a model. The maximum gradients needed are 600 to 700

gauss/in. A very good approximation of the desired field vs radius for a 240-in. cyclotron unit design is shown in Fig. 5.23. It should be noted that the field was obtained with pole tips having only two slopes. The gap varies from 5 in. at the 224-in. radius to 30 in. at the 174-in. radius. The 30-in. gap near this radius is about the maximum that can be used and still obtain the required flutter. At smaller radii the gap must be reduced to a minimum, until near the center a 5-in. gap is wider than desired if flutter were the only criterion. There is little question that either of these methods or a combination of them can be used to design a magnet, but at this time

Fig. 5.17. Proposed Site of the Mc^2 Cyclotron with Respect to Other Laboratory Installations.

neither of the methods gives any promise of providing a significant reduction in power or steel, as compared with the method used for the initial 0.15-scale model incorporating radial gradient coils.

A tentative conclusion is that a combination of methods will be used in the final design. Obtaining the magnetic-field gradients at the outside edge of the magnet by shaping the steel has the distinct advantage that the magnet coils may be removed from the gap, thus substantially reducing radiation damage to the coil insulation.

RF Cavity Tests. — The Mc^2 cyclotron radio-frequency system will operate at a frequency of about 14 Mc/sec, the second harmonic of the cyclotron frequency. With four accelerating gaps per revolution the maximum energy gain per turn will be 1 Mev. Cavity resonators rather than conventional dcc structures will be used; cavities fitting between the magnet sectors occupy no magnet gap space and permit a more economical magnet design. Also, the excitation power is less for cavity resonators, and the gap voltage can be made reasonably constant with radius.

Either a pair of TE or a pair of coaxial (TEM) cavities is suitable for the Mc^2 cyclotron. Models of these cavities were constructed and tested; they are shown in Fig. 5.24. The various characteristics of the models measured are given in Table 5.2. The large discrepancy between measured and theoretical Q for the coaxial model is attributed to the pressure contact employed along the short-circuited ends and to the sharp corners around its periphery. The higher-order resonance modes observed in the coaxial cavity model produced voltage variations around the periphery of the cavity; they should present no problem, however, since they are at a considerably higher frequency than the desired mode.

A model of a "partial" or "auxiliary" cavity which could be used to increase the energy gain at larger radii was also tested. The configuration of this model and results of the tests are shown in Fig. 5.25.

The rf amplifier and coupling network for the Mc^2 were examined briefly; one feasible system is shown in Fig. 5.26. The power amplifier consists of two RCA 6949 super-power triodes operating in push-pull; it should be capable of

Fig 5.18. Topography of Proposed Site.

Fig. 5.19. Magnetic Field vs Azimuth in 0.15-Scale Model.

Fig. 5.22. Flutter vs Radius.

Fig. 5.20. Peak Field vs Radius.

Fig. 5.21. Average Field vs Radius.

Table 5.2. Characteristics of Model rf Cavities

	TE Model	Coaxial Model
Measured Q	4500	1800
Theoretical Q	4500	4500
Voltage variation along gap	$\pm 5\%$ min (function of tuning)	$\pm 5\%$
Tuning range, Mc/sec	149 to 160	139 to 152
Observed resonances, Mc/sec	158, 253, ---	152, 193, 220, 286, ---

supplying at least 800 kw of rf power. Since the power amplifier would be located outside the cyclotron vault, the transmission line would be about 100 to 200 ft long. If the line is matched to the load, then the length would be unimportant; it would be advantageous, however, to make the line an integral number of half wavelengths to ease the problem of sparking in the cavity. A driver-resonator model is being constructed to study the transient behavior of the system.

Facilities for the Muon Beam. — One of the main features of the ion-optics system proposed for the Mc^2 cyclotron is the availability of a high-intensity muon beam. The design of the facilities for such a beam must rely on the properties of the $\pi \rightarrow \mu$ decay characteristics. Pions with a

Fig. 5.23. Data from Model Magnet with Tapered Gap.

rest-frame mean life of $\tau_\pi = 2.56 \times 10^{-8}$ sec decay to muons. A pion of velocity v_π will travel a mean distance of $v_\pi \gamma_\pi \tau_\pi$ before decaying, where $\gamma_\pi = (1 - v_\pi^2/c^2)^{-1/2}$. Thus the mean flight path for pions of 420 Mev kinetic energy (nearly the highest pion energy expected for the Mc² cyclotron) would be about 100 ft.

In their own rest frame, pions give rise to monoenergetic muons with an isotropic probability distribution in space. When the pions decay while in motion, the angular distribution of emitted muons becomes peaked in the forward direction in the laboratory system; for sufficiently energetic pions, the muon distribution is restricted to lie within a cone about the pion direction. The half angle θ for the cone is given by

$$\theta = \tan^{-1} \frac{1}{\gamma_\pi \sqrt{(v_\pi/v'_\mu)^2 - 1}},$$

where v_π is the pion velocity in the laboratory system, and v'_μ is the velocity of the muon in the rest frame of the pion. The cone half angle θ is shown in Fig. 5.27 as a function of pion kinetic energy. This spread of the muon directions from the original pion direction, combined with the spread inherent in the original

pion beam, produces a very divergent muon beam.

Another important feature of the $\pi \rightarrow \mu$ decay kinetics is that a monoenergetic beam of pions yields muons with an energy-independent distribution which extends from

$$(\gamma_\pi \gamma'_\mu - 1) m_\mu c^2 - v_\pi \gamma_\pi P'_\mu$$

to

$$(\gamma_\pi \gamma'_\mu - 1) m_\mu c^2 + v_\pi \gamma_\pi P'_\mu,$$

where m_μ is the muon rest mass and P'_μ is the muon momentum in the rest frame of the pion. With this energy spread the pions and muons can be readily separated by momentum analysis.

Muon beams have been produced in two radically different arrangements at existing cyclotron facilities. The so-called "mu-meson channel" arrangement consists of a set of many identical and equally spaced quadrupole magnets.⁸ The channel is designed to trap and transmit muons arising from the in-flight decay of pions while

⁸A. Citron *et al.*, "A High-Intensity μ -Meson Beam from the 600-Mev CERN Synchrocyclotron," *Instrumentation for High-Energy Physics, Proceedings of an International Conference*, p 268, Interscience, New York, 1961.

Fig. 5.24. Model RF Cavities. (a) TE cavity; (b) coaxial cavity.

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Fig. 5.25. Auxiliary Cavity and Voltage Distribution. (a) Auxiliary cavity, (b) test data.

Fig. 5.26. Possible Power Amplifier and Coupling Network for the Mc^2 .

Fig. 5.27. Half Angle of Muon Cone as a Function of Kinetic Energy of Parent Pions.

they are traveling down the channel. As a result the channel has rather poor transmission properties with respect to particles produced at a point source before the entrance.

A different method for forming a muon beam uses a simple system of two quadrupole doublet lenses and a bending magnet.⁹ Operation of this system is based on collecting and focusing to an image the muons produced in the neighborhood of the pion source. Such a system can have a sizable transmission for particles produced near the source but essentially no trapping properties for particles produced by in-flight decay beyond the target. This system is also quite momentum-selective and can be easily "tuned" to a variety of particle momenta.

⁹G. M. Bingham, *Measurement of G/M for Muons*, UCRL-10107 (1962).

A precise comparison of the above two methods for producing muon beams is difficult because of different primary beam conditions, different targets, and different geometries. Roughly, the muon intensities available from the two facilities appear to be of the same order of magnitude; however, mu-meson channel design results in pion contamination of the muon beam which is several orders of magnitude less than that obtained in the two-lens system. To be sure, the latter beam could be further purified by various methods but at a sacrifice of muon intensity. Since a high-purity muon beam is necessary for many types of experiments, the channel design is preferred for a versatile muon facility.

SEPARATED-ORBIT CYCLOTRON

A preliminary study¹⁰ is being made of a new particle accelerator concept incorporating strong focusing and other attractive features. The major innovation in this machine is that the ions follow a spiral-helix orbit as indicated in Fig. 5.28.

¹⁰F. M. Russell, "A Fixed-Frequency, Fixed-Field, High-Energy Accelerator," *Nuclear Instruments and Methods*, in press.

Fig. 5.28. Diagram of Beam Path with Both Radial and Axial Separation. Accelerating gaps are indicated by dots along the beam path. The rf voltages at the gaps joined by dashed lines are in phase.

Acceleration is achieved by repeated passage of the ions through several rf cavity structures placed at regular angular intervals about the machine axis. The rf electric fields produced within these structures at the acceleration gaps are represented by dots in Fig. 5.28. The particles are

confined to oscillation about an equilibrium orbit by using alternating gradient components superposed on a steady magnetic field.

One method for generating such a magnetic field is indicated in Fig. 5.29. The main magnetic field is generated by coils individually wound on steel blocks and arranged in a near-vertical stack. In this way, vertically adjacent coils assist in generating the fields between the steel blocks. Tapered iron shims, mounted in pairs upon the blocks, produce the alternating gradients in the field. Figure 5.29 also indicates the relative positions of the magnet stacks and the rf cavities. The cavities consist of copper resonators operated in their lowest mode with the electric field parallel to the ion flight path. At the working frequency, ions take one-half an rf cycle in passing between successive acceleration gaps. A sketch of such a cavity is shown in Fig. 5.30.

By choosing the appropriate energy gain per gap crossing and the mean strength of the magnetic field as a function of the energy of an ion, it is possible to make the period of rotation constant (isochronous).

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Fig. 5.29. Sketch of a Complete Magnet and RF Cavity Sector. Each sector contains one rf cavity and pairs of magnet cells, the positive and negative gradient sections being mounted upon a common support so that the magnet pairs can be accurately aligned. The entire accelerator consists of N such units, so arranged as to form a closed path. The slight changes required in each cell to allow for the increasing energy of the ions are obtained by placement of the shaped magnet shims on the pole faces.

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Fig. 5.30. Sketch of Cavity Showing Successive Passes of the Spiraled Ion Path.

It can be shown that a machine of this type exhibits the following properties:

1. continuous beam output (as in a cyclotron),
2. high transverse stability (by strong-focusing action),
3. phase stability in longitudinal motion. (as in a synchrotron),
4. whole beam conveniently extracted (as in a linac),
5. output energy varied in steps (as in a linac),
6. no serious instability resonances,
7. good extracted beam quality.

A preliminary design study¹¹ for such a machine to accelerate 1 ma of protons to 1000 Mev is being prepared.

¹¹F. M. Russell, *A Strong-Focusing Cyclotron with Separated Orbits*, ORNL-3431, to be published.

6. The Oak Ridge Isochronous Cyclotron¹

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The preliminary testing of the Oak Ridge Isochronous Cyclotron (ORIC) at full radius but at nominal power was completed. The power amplifier was then installed (see Fig. 6.1), and the machine is being readied for operation at full power.

The cyclotron is a 76-in., three-sector, azimuthally-varying-field, variable-energy machine. It is designed to accelerate various particles, within the e/m ratio of 1 to 0.125, to energies up to 145 Mev. Ample rf power has been provided to handle large beam currents, with 1 ma of protons at 75 Mev being a typical design maximum.

Early this year a temporary rf system was installed so that the orbit dynamics of the machine could be studied while the design and fabrication

of the permanent power amplifier were being completed. With this system a program of test operation at reduced dee voltage and beam energy simulated most of the problems of full-energy operation, but with more-tractable radiation conditions. Protons are held in phase for at least 500 revolutions, which is substantially in excess of the design value of 375.

During the testing program the internal beam was successfully brought through an electrostatic deflector channel. The machine was then shut down, and a permanent high-power rf system was installed; final preparations are being made for testing at full power.

ORIC MAGNETIC FIELD

To achieve isochronous acceleration of ions over the large number of turns required in ORIC, it is necessary to maintain the radial gradient of the average magnetic field within a close tolerance. The shape of the radially increasing field is controlled by ten pairs of circular trimming coils (see Fig. 6.2). Three methods of achieving proper adjustment of the currents in these coils were used successfully: (1) the current settings were computed from the magnetic-field measurements; (2) the currents were adjusted while the magnitude of the beam current was monitored on a movable probe; and (3) the currents were adjusted while the phase of the beam current was monitored on a movable probe specially developed for this purpose. The three basic methods can also be used in combination. The current settings obtained

¹Several papers describing features of the Oak Ridge Isochronous Cyclotron were presented at the International Conference on Sector-Focused Cyclotrons, Los Angeles, April 17-20, 1962, and published in the proceedings: R. H. Bassel, R. S. Bender, and J. G. Innes, "Analyzing Methods for ORIC Magnetic Fields," *Nucl. Instr. Methods* 18-19, 303 (1962); R. J. Jones, "Remarks on Tune-Up of Analogue II," *Nucl. Instr. Methods* 18-19, 469 (1962); R. J. Jones *et al.*, "Unique Features in the Oak Ridge Isochronous Cyclotron," *Nucl. Instr. Methods* 18-19, 46 (1962); R. S. Livingston *et al.*, "Concepts of an Mc² Cyclotron," *Nucl. Instr. Methods* 18-19, 438 (1962); J. A. Martin and J. E. Mann, "Beam Characteristics in Cyclotron Analogue II," *Nucl. Instr. Methods* 18-19, 461 (1962); W. H. White, Jr., B. Duelli, and R. J. Jones, "Beam-Phase Measurement Studies," *Nucl. Instr. Methods* 18-19, 601 (1962).

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⁵Instrumentation and Controls Division.

Fig. 6.1. Power Amplifier and Other RF Components Mounted on Top of the Dee-Stem Housing.

by several methods of optimization are shown in Table 6.1. The phase probe is a very effective aid in optimizing the magnet currents.

DEFLECTION SYSTEM

The deflection system includes four subassemblies placed within the cyclotron accelerating tank. The electrostatic channel performs the initial separation of the deflected beam from the circulating beam. During tests last June, approximately 30% of the circulating beam was brought through this channel, which consisted of a $\frac{1}{16}$ -in.-thick slotted-graphite septum and an uncooled aluminum deflector electrode, spaced $\frac{1}{2}$ to $\frac{5}{8}$ in.

Radioautographs of the circulating and deflected beams are shown in Fig. 6.3. Measurements of beam quality by radioautograph and by melted-foil techniques indicate that there is no large axial or radial divergence through the electrostatic deflector. A series of melted foils is shown in Fig. 6.4.

Following the deflector are the first and second sections of the magnetic channel, which reduce the magnetic field along the path of the deflected beam. After passing through the channels the beam enters the No. 1 beam-positioning magnet, which reinforces the fringing field to give the beam the proper angle for entrance into the external ion-optics system.

The first section of the magnetic channel is of "coaxial" design to minimize the field disturbance

Fig. 6.2. Sketch of ORIC Magnet with One Pole Tip Exploded to Show Associated Coils.

Table 6.1. Currents in Circular Coils as Optimized by Various Methods, with Test Conditions and Results

	Optimized from			Computed		Limit
	Beam Current	Phase Probe	Phase + Current	Direct	Experimental Adj	
Circular coils, amp						
Coil 1	+356	+371	+357	0	0	1080
2	-529	-540	-560	-465	-424	900
3	0	+133	+104	+208	+123	801
4	+203	+86	+136	0	0	700
5	+120	+74	+68	+258	+303	675
6	+333	+333	+334	+162	+115	550
7	+314	+355	+347	+434	+436	550
8	+422	+439	+469	+515	+506	515
9	+183	+229	+285	+266	+280	490
10	-445	-415	-435	-470	-461	470
Test conditions						
Dee voltage, kv	15	10	10	12	12	
Radius (max), in.	33	32	34	24	34	
Beam measured						
At $R = 32$ in., μ a	65	100	180		110	
At $R = 20$ in., μ a	305	370	260		190	

in the region of the circulating beam immediately external to the channel. This channel is in the process of fabrication (see Fig. 6.5). The principle of operation is illustrated in Fig. 6.6. The total excitation in the inner and outer conductors is 200,000 ampere-turns; the field reduction in the beam space is about 6 kilogauss. The circulating beam will travel essentially undisturbed in the notched area of the outer conductor, less than an inch from the deflected beam.

The second section of the magnetic channel moves the deflected beam still farther from the circulating beam. Since more space is available, a more conventional design is being prepared for this section.

ORBIT STUDIES

The size and location of the first- and second-harmonic magnetic-field bumps were studied. It was shown that asymmetrical excitation of the valley coils could give the beam the radial gain per turn required to enter the electrostatic channel. The shape of the deflector was determined and also the strength and location of the magnetic channel needed to extract the beam.

A complete catalog of coil currents and orbit properties was calculated for protons, alpha particles, and nitrogen ions at nine different energies. This should serve as a useful guide in cyclotron operation.

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CIRCULATING BEAM
AT $R = 25$ in.

DEFLECTED BEAM
AT EXIT OF
ELECTROSTATIC CHANNEL

Fig. 6.3. Radioautographs of Beam, Made During Preliminary Testing Program.

RADIO-FREQUENCY SYSTEM

Early this year the dee and the dee-stem transition were mounted on the end of the 50-in.-diam center conductor of the resonator. This was preceded by a careful alignment procedure to ensure that the dee would come to rest centered in the gap and parallel to the pole-tip faces. While the components were held in position by bolts and shims, the circumferential joint was permanently Heliarc welded with copper.

A temporary rf system, using a 4CX-5000A, as the final amplifier, was installed and used for the test operations. The system was controlled from a temporary console in the control room, which allowed motorized tuning of the intermediate amplifier, final amplifier, and resonator trimmers. Phase detectors were used for indicating resonance of amplifiers. An rf voltmeter was used for indicating resonance of the dee system.

The temporary rf system was operated at 7.8 Mc with the dee voltage as high as 18 kv peak-to-ground. This was the maximum voltage that could be obtained within the plate dissipation rating of the 4CX-5000A. During the three months of test operation no attempt was made to increase the frequency; the increased power requirements would have limited the dee voltage to an unreasonably low level. The dee-voltage waveform was observed to be free of modulation and harmonic distortion. This indicates good mechanical stability in the resonator structure.

The initial test program was terminated in July for installation of the permanent power amplifier. This amplifier, including its local control panel, was assembled and placed in position on top of the resonator. The entire system was then raised into position and attached to the support legs of its handling crane, as shown in Fig. 6.1. Since the crane also has x and y translation in a

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Fig. 6.4. Sequence of Foils Melted by Deflected Beam, Moving Right to Left.

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Fig. 6.5. Coaxial Magnetic Channel, Partially Assembled. For design see Fig. 6.6.

Fig. 6.6. Cross Section of Coaxial Magnet, Showing Sharp Field Cutoff.

horizontal plane, all leads and services were made flexible, or detachable, to provide freedom of motion.

The permanent power amplifier, which uses an RCA 6949, was designed, fabricated, installed, and tested. The grid circuit is a pi network with both L and C variable. Most of the tuning is accomplished by positioning a shorting plane which adjusts the lengths of the $\frac{1}{4}$ -wave lines extending from the driver-amplifier plate and the power-amplifier grid (see Fig. 6.7). Fixed capacitors are inserted at the driver-amplifier plate and power-amplifier grid for operation between 7 and 11 Mc; they are withdrawn for operation between 11 and 23 Mc. Fine tuning is obtained with a variable capacitor on the driver-amplifier plate (see Fig. 6.8).

The tank circuit of the power-amplifier plate has a variable inductance formed by a length of coaxial line with a movable shorting plane, also shown in Fig. 6.7. The line is padded by a gang of four variable capacitors. Only the capacitors are used with the automatic servo for fine tuning, but in selecting a frequency for operation, both inductance and capacitance are varied to maintain a constant L/C ratio.

Water cooling for the plate and grid inductors and forced-air cooling for the external ceramic surface of the power-amplifier tube are provided, in addition to the usual internal water cooling required by the RCA 6949.

Controls for the rf system (Fig. 6.8) were designed, installed, and tested. Complete control of the system is possible from either the master console in the control room or from the local controls on the side of the resonator. The resonator and amplifier stages (Fig. 6.9) can be tuned either with manual controls or by automatic servos.

There are four automatic tuning servos (see Fig. 6.10). These include trimmer tuning, power-amplifier plate capacitance tuning, driver-amplifier plate capacitance tuning, and intermediate-amplifier capacitance tuning. Four additional servos, which are presently manually controlled, are the driver-amplifier plate inductance servo, the power-amplifier plate inductance servo, the resonator-drive capacitor positioning servo, and the resonator-shortening-plane positioning servo. Controls for automatic operation of the latter four units have been designed and will be installed. It is necessary to manually tune the automatic servos to a region near the resonance condition before they will operate automatically. A preset tuning system was designed for this purpose and will also be installed.

Automatic voltage regulators were designed and installed in both the power-amplifier filament power supply and the dc filament supply used with the driver-amplifier and intermediate-amplifier filaments.

Plug-in circuits are used extensively in the filament regulators and in the tuning servos. Failure of any of these units can be quickly corrected by replacement with a spare circuit board.

The completed rf system has been operated at several frequencies with dee-to-ground voltage as high as 75 kv. Higher voltages will be attempted as the checkout program progresses. The system operates quite easily; high rf voltage appears on

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Fig. 6.7. Power Amplifier. The grid tank circuit extends forward from beneath the housing of the plate tank circuit. The RCA 6949, suspended at the left, will be placed inside the central conductor of the variable transmission line of the plate tank circuit. One of the four variable vacuum capacitors for fine tuning of the plate tank circuit is shown on the filament transformer at the right.

Fig. 6.8. Driver-Amplifier Plate Capacitors. The large central capacitor can be varied for fine tuning the circuit.

Fig. 6.9. Block Diagram of RF Amplifiers and Regulator Circuits.

the dee as soon as the entire system is in resonance. No multipactoring or ion-loading problems have been encountered.

A transistorized version of the master signal generator was designed and tested. This unit is expected to be more reliable than the existing vacuum-tube version, but fabrication and installation are optional.

Regulators for the power-amplifier dc plate voltage and the rf dee voltage were designed. Since these units are not vital to operation of the rf system, their fabrication has been temporarily delayed. The power-amplifier dc plate voltage regulator will permit the plate voltage supply to automatically run up to a preset value whenever it is turned on, or reset after firing of the protective crowbar. The dee-voltage regulator would eliminate any modulation present in the rf-voltage waveform on the dee.

ORIC OPERATIONS

The operations group started 24-hr coverage for five days a week in early March. This coincided with the start of initial testing of the machine. The various stages included: getting operable pressures, establishing adequate cooling to the various components, stabilizing the rf excitation, and accelerating and deflecting a proton beam. The best vacuum obtained at this time was $\sim 1.9 \times 10^{-6}$ torr, with a rate of rise of $\sim 0.00045 \mu/\text{sec}$.

The first internal proton beam at full radius of 31.5 in. was obtained on March 18, 1962. The proton energy, 8.0 ± 0.1 Mev, was verified by the well-known stacked-foil technique; the 38-min activity was measured from the reaction $\text{Cu}^{63}(p,n)\text{Zn}^{63}$, for which the threshold is 4.2 Mev.

The testing program continued for about three months, during which time numerous internal-beam

Fig. 6.10. Automatic Tuning Servomechanism for RF System.

studies were made in an effort to determine the machine's operational characteristics.

Following the installation of the permanent power amplifier, operational checkout and testing of the new system were begun in October. By December 20 a stable dee-to-ground potential of ~ 50 kv was maintained. With this initial success, it is expected that high-energy beams will become available in the ORIC in January 1963.

ION OPTICS

The elements of the external ion optics necessary for transmitting the beam into the small experiment room are nearly completed and ready for installation. They include the No. 1 quadrupole, the vertical positioning magnet, and the No. 1 (45°) beam switching magnet (see Fig. 6.11). Other necessary quadrupole lenses and the power supplies are now on order.

POWER SUPPLY SYSTEMS

Magnet Power Supplies

The 19 power supplies for the pole-face coils which shape the isochronous field were checked out; they were used during cyclotron testing. Failures of certain air-cooled rectifier diodes, due to overheating, prompted mounting these diodes on water-cooled heat sinks. Since this has worked quite well, water cooling will be installed on all units as soon as possible.

Ion-Source Supplies

Power supplies for the ion-source filament and arc were installed and operated. These units were obtained as surplus from electromagnetic separation units (Y-12) and were modified for operation in the cyclotron. The arc current is controlled by varying the filament power.

Fig. 6.11. The No. 1 (45°) Beam-Switching Magnet.

Deflector Power Supply

A 120-kv, 30-ma, power supply for the electrostatic deflector was purchased and installed. It was found that incorporation of a 1-megohm series resistor at the end of the cable nearest the deflector greatly improves the ability of the deflector to hold voltage. Up to 80 kv has been applied to the deflector.

CYCLOTRON CONTROL SYSTEM

With the installation of the rf-system controls in the control room, the central cyclotron control station at the console is nearly complete. Controls for external ion handling are not yet installed and operating, but these will be completed as the ion-optics systems are installed. Vacuum controls and beam-pipe valving, beam-handling magnets and power supplies, and beam plugs and stops are being built or purchased.

PHASE-PROBE SYSTEM

A system for measuring the phase of the circulating ion beam with respect to the applied rf voltage was developed and tested. It measures the phase of the bunched ions in the beam without in any way disrupting the beam. The system, shown in Fig. 6.12, consists of a shielded pickup plate which detects the electromagnetic wave created by the motion of ions in the beam. The signal developed on this line is fed to a sampling oscilloscope which is triggered by an rf signal sampled from the dee. Oscilloscope measurement of the phase is made by observing the relative displacement of the rf waveform and the beam-induced waveform (see Fig. 6.13).

The system proved very valuable for adjusting the currents in the various coils in the magnet to achieve isochronism. Beam phase can be observed and measured at any radius from 3 to 34 in. A system of fixed probes will be installed at various radii in the machine to aid in maintaining isochronism during operation.

Fig. 6.12. Scheme Used for Beam-Phase Measurements.

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PHOTO P-57083

Fig. 6.13. Beam-Phase Waveforms at Various Radii. The sweep is 10 nanoseconds/cm and the vertical sensitivity 10 mv/cm.

7. Superconducting-Magnet Development

R. W. Boom
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S. T. Sekula³

Three of the basic problems connected with the design of large niobium-zirconium superconducting magnets were investigated during the year. These are "current degradation," protection and safety, and transitions to the normal state.

Current degradation refers to the puzzling anomaly of current capacity. It was found early at many laboratories, including ORNL, that most small-bore magnets made of 0.010-in. Nb-25% Zr wire carry only about 20 amp for all fields below critically high fields, even though short-wire tests seemingly indicate much higher currents should be expected. Later it was found that 20 amp is not an invariant, but that it decreases as the diameter of the magnet is made larger, and that it also depends on other factors. Techniques mentioned below show that the 20-amp capacity can be increased.

Protection and safety refers to the transition of a magnet from the superconducting state. It was found that transitions initiate at one point, propagate at thermal velocities, and heat the wires by Joule heating. As a result the field decays with a time constant L/R . This produces voltages large enough to damage insulation; it also results in overheating of the conductor, commonly with melting at the first point of transition.

Basic to the understanding of superconducting magnets and to the solution of associated problems are detailed measurements of all quantities, electrical and thermal, which describe the transition. Interpretation of our measurements is presented below.

MAGNET TESTS

A series of $\frac{1}{2}$ -in.-ID test magnets potted in epoxy resin produce 15 to 30 kilogauss and carry 29 to 30 amp, an increase of 50% over the usual 20-amp capacity of unpotted magnets. An obvious advantage of epoxy potting is that the epoxy provides solid thermal contact to a massive medium.

The ORNL magnets are usually bifilar wound with 20% of the volume nylon-insulated 10-mil Nb-Zr wire, 20% Formvar-insulated 10-mil copper wire, and 60% epoxy. Some magnets are wound on copper forms and some on brass forms, but most are on epoxy forms. The copper secondaries supply protection during field collapse by absorbing a large fraction of the field energy, $\frac{1}{2} LI_0^2$, and by slowing down the rate of decay, thus reducing induced voltages.

For a magnet study, the copper secondary, in 1:1 coupling with the primary, supplies a very convenient method for measuring the Nb-Zr resistance as it develops. If the Nb-Zr primary and the copper secondary are both separately shorted, but disconnected from other circuitry and from each other, then

$$I_p R_p = I_s R_s.$$

Since I_p , I_s , and R_s are easily measured as functions of time, R_p can be known as a function of time. It is found that, in the transition from the superconducting to the normal state, the resistance of the primary increases linearly with time; that is,

$$R_p \approx \alpha t,$$

where α ranges from 10^3 to 10^4 ohms/sec for this type of construction.

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³Solid State Division.

Oscilloscope traces of I_p and I_s during a field collapse are shown in Fig. 7.1; the computed R_p and energy dissipation are given in Fig. 7.2. It is seen that only 5% of the energy is dissipated in the Nb-Zr primary. It can be shown that an approximate expression for I_p during the field collapse is

$$I_p = I_0 \frac{e^{-tR_s/L}}{1 + \alpha t/R_s}, \quad \text{for } R_p = \alpha t.$$

Most of the energy stored in the Nb-Zr windings is dissipated promptly; if $t \leq 10R_s/\alpha$, the energy dissipated in the Nb-Zr is

$$E(\text{Nb-Zr}) = 1.5I_0^2 R_s^2 / \alpha \text{ joules}.$$

For our magnets, $R_s \cong 1 \text{ ohm}$, $\alpha \cong 10^3 \text{ ohms/sec}$, and $I_0 \cong 30 \text{ amp}$; so $E(\text{Nb-Zr}) \cong 1.5 \text{ joules}$. It is best to distribute this energy as widely as possible; thus the copper should be of high purity

(low R_s), and the construction should be such that α is as large as possible.

At the point of initial transition the energy dissipated per unit length is

$$E/\text{cm} = 0.06(R_s/\alpha)I_0^2 \text{ joules}.$$

The energy required to increase the temperature of the Nb-25% Zr (initially at 4.2°K) by 300°K is calculated⁴ to be 55 joules/g. Thus, to ensure that no point in the sample goes above room temperature, the energy dissipated should not exceed 0.2 joule/cm.

The voltage across the normal part of the Nb-Zr is

$$V \cong I_0 R_s \frac{e^{-tR_s/L}}{1 + R_s/\alpha t}.$$

⁴P. Smith, Harwell, private communication.

Fig. 7.1. Field Collapse in Magnet B with the Secondary Closed. Time base is 0.050 sec/cm. Upper trace is primary (Nb-Zr) current; lower trace is secondary current, at 10 amp/cm.

Fig. 7.2. Data from Field Collapse in Magnet B with Secondary Closed. Primary and secondary currents, power, and resistance as computed from Fig. 7.1.

Table 7.1. Test Magnets (0.010-in. Nb-25 at. % Zr)
Temperature, 4.2°K

	Magnet						
	A, Open Winding	B, Secondary, Epoxy		C, Secondary, No Epoxy		D, Secondary, Epoxy	
		Closed	Open	Closed	Open	Closed	Open
Current, max (amp)	18	34	18	24	24	32	16
Field, max (kilogauss)	29	20	10.6	17.5	17.5	28	14
Wire length (ft)	1800	1000		850		1700	
Winding density (turns/cm ²)	950	300		469		333	
Inductance (henries)	0.37	0.13		0.098		0.25	
Size (in.)							
ID	1/2	1/2		1/2		1/2	
OD	2	2 1/2		2		2 1/2	
Length	1 1/4	1 1/2		1 1/4		2	

For low voltages, R_s should be small and the time constant L/R_s should be long.

The magnets built and tested are shown in Table 7.1. Magnet A was wound without epoxy or secondary and carried the expected 18 amp. Magnet C, with a secondary but without epoxy, carried slightly more current but not as much as magnet B, which was potted in epoxy. Magnet D, also potted in

epoxy, was destroyed during the first tests with the secondary open, confirming the above-mentioned safety limits. Also, another magnet, with 2-in. ID, $1\frac{1}{2}$ -in. length, and $3\frac{3}{4}$ -in. OD, was wound on an epoxy form with a copper secondary and potted in epoxy. It carries a maximum of 38 amp and produces 14 kilogauss at the center and 18 kilogauss maximum on any winding. The measurements show

that $\alpha \approx 10^3$ ohms/sec; it should be similar to other α 's because the thermal conditions are similar.

MATERIALS EVALUATION

Various superconducting alloys were evaluated in the ORNL High-Field Solenoid, which provides

Fig. 7.3. Transverse Field Tests of Commercially Available 10-Mil Nb-Zr Wire of Varying Compositions.

Fig. 7.4. Longitudinal Field Tests of Commercial 10-Mil Nb-Zr Wire of Varying Compositions.

fields up to 100 kilogauss. Results for commercial 10-mil Nb-Zr wire are shown in Fig. 7.3. The Nb-25% Zr is the standard Wah Chang product with over 99.9% reduction in area during the initial drawing and swaging processes. The Nb-33% Zr is a selected best sample which was heat-treated at 790°C for 15 min before drawing. The Nb-50% Zr is a selected best sample heat-treated the same way. The only available sample of Nb-75% Zr was not heat-treated.

Short-wire longitudinal tests were made for Nb-Zr (Fig. 7.4), Ti-Ta (Fig. 7.5), and Mo-Re (Fig. 7.6). All tests showed large peaks in the current capacity of the wire at intermediate field intensities. It is speculated that this behavior is due to helical (possibly force-free) current flow. A toroid was constructed to confirm these results. One layer of 10-mil wire was wound on a 4-in.-diam, $\frac{1}{2}$ -in. cross-section form so that each wire was at 45° to a radius vector. This is the prescription for making a force-free toroid in which the current sheet and the field are everywhere parallel. A maximum current of 120 amp was carried in a local self field of about 4 kilogauss. Inspection of Fig. 7.4 shows that the current in the parallel field should have been about 240 amp. This high current tends to confirm short-wire tests; construction difficulties which prevent perfect 45° sheet flow may account for the difference noted.

Fig. 7.5. Tests of Ti-Ta Wire in Longitudinal Field.

Tests with small four- to eight-layer magnets in external fields confirm earlier results; that is, the peaks in the I - H curve are similar to those found for longitudinal samples. Typically, a small $\frac{1}{2}$ -in.-ID, 1-in.-long, eight-layer magnet of Nb-25% Zr 10-mil-diam wire will carry 20 amp in its self field, 40 amp in an external field of 20 kilogauss, and approximately the same currents predicted by transverse short-wire tests in external fields higher than 20 kilogauss. This peaking indicates that in large Nb-Zr magnets, the region in which a superconducting-to-normal transition initially occurs could be in either a high- or a low-field region of the windings. Possibilities of optimizing the current capacities of superconducting magnets will be evaluated with a multisection magnet now under construction.

Fig. 7.6. Test of a Sample of Mo-Re Wire in Longitudinal Field.

Papers Presented at Scientific and Technical Meetings

American Physical Society, New York, January 24-27, 1962

J. B. Ball, C. D. Goodman, and C. B. Fulmer, "A Comparison of Cross Sections for (p, d) , (p, t) , and (p, α) to the Same Final States."

C. B. Fulmer, J. B. Ball, and C. D. Goodman, " (p, t) Reactions in Zirconium Isotopes."

C. D. Goodman, C. B. Fulmer, and J. B. Ball, " (p, d) Reactions in Zirconium Isotopes."

J. W. Wachter, "Differential Cross Sections of the $\text{Li}^6(\text{N}^{14}, \alpha)\text{O}^{16}$ and $\text{Li}^7(\text{N}^{14}, \alpha)\text{O}^{17}$ Reactions."

Southeastern Section of the American Physical Society, Tallahassee, Florida, April 5-7, 1962

J. B. Ball, C. D. Goodman, and C. B. Fulmer, "The Nuclear Deformation of Mn^{55} Inferred from the $\text{Mn}^{55}(p, d)$ Reaction with 22-Mev Protons."

C. J. Bergeron, L. D. Roberts, and R. W. Boom, "Superconducting Tests of NbZr in a High-Field Magnet."

R. W. Boom and L. D. Roberts, "Transformer-Type Limiting of the Transition Rate in a Superconducting Magnet."

C. B. Fulmer, J. Benveniste, and A. Mitchell, "Proton Scattering by Ni^{64} and Zn^{64} at 9.6 and 11.7 Mev."

J. A. Martin, G. L. Broyles, and J. E. Mann, "Magnetic Field Design for Cyclotron Analogue II."

E. Newman and K. S. Toth, "Nitrogen-Induced Nuclear Reactions in Chlorine."

L. D. Roberts and R. W. Boom, "Studies on a 33-kgauss Superconducting Magnet."

International Conference on Sector-Focused Cyclotrons, Los Angeles, April 16-19, 1962

R. H. Bassel, R. S. Bender, and J. G. Innes, "Analyzing Methods for ORIC Magnetic Fields."

R. J. Jones, "Remarks on Tune-Up of Analogue II."

R. J. Jones, E. D. Hudson, R. S. Livingston, R. S. Lord, M. B. Marshall, W. R. Smith, W. H. White, Jr., and R. E. Worsham, "Unique Features in the Oak Ridge Isochronous Cyclotron."

R. S. Livingston, E. D. Hudson, R. J. Jones, R. S. Lord, J. E. Mann, J. A. Martin, F. M. Russell, N. F. Ziegler, and A. Zucker, "Concepts of an Mc^2 Cyclotron."

J. A. Martin and J. E. Mann, "Beam Characteristics in Cyclotron Analogue II."

W. H. White, Jr., B. Duelli, and R. J. Jones, "Beam-Phase Measurement Studies."

American Physical Society, Washington, D.C., April 23-26, 1962

R. H. Bassel, R. M. Drisko, E. Rost, and G. R. Satchler, "Analysis of the Inelastic Scattering of Alpha Particles."

C. D. Goodman, J. B. Ball, and C. B. Fulmer, "Interpretations of Low-Lying Levels in Zirconium Isotopes Inferred from (p, p') , (p, d) , and (p, t) Spectra."

M. L. Halbert and F. E. Durham, "Angular Momentum Effects in Compound Nucleus Reactions."

E. Newman and K. S. Toth, "Some Single-Nucleon Transfer Reaction Cross Sections Obtained with 27.5-Mev N^{14} Ions."

K. S. Toth, "The Angular Distribution and Ranges of N^{13} Particles Resulting from 27.5-Mev N^{14} Ions on Mg^{24} ."

A. Zucker and B. Linder, "Radiative Capture of N^{14} on P^{31} ."

E. C. Halbert, R. H. Bassel, and G. R. Satchler, "Optical Model Analysis of Elastic Deuteron Scattering."

High-Energy Instrumentation Conference, Geneva, July 16-18, 1962

R. W. Boom, L. D. Roberts, and R. S. Livingston, "Developments in Superconductor Solenoids."

International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padova, Italy, September, 3-8, 1962

J. B. Ball, C. B. Fulmer, and C. D. Goodman, "A Comparison of (p,d) , (p,t) , and (p,α) Reactions Exciting the Same Final States."

A. Zucker (invited paper), "Reactions in the Nuclear Surface."

Conference on Utilization of Multiparameter Analyzers in Nuclear Physics, Grossingers, Liberty, New York, November 12-15, 1962

D. A. Bromley, C. D. Goodman, and G. D. O'Kelley, "Multi-Parameter Analysis in Accelerator Studies in Nuclear Physics."

C. D. Goodman, G. D. O'Kelley, and D. A. Bromley, "Examining and Processing Multiparameter Data from the ORNL-Yale Analyzers."

G. D. O'Kelley, D. A. Bromley, and C. D. Goodman, "The Role of Multiparameter Pulse-Height Analyzers in Radioactivity Studies."

Publications

Bassel, R. H., R. S. Bender, and J. G. Innes, "Analyzing Methods for ORIC Magnetic Fields," *Nucl. Instr. Methods* **18-19**, 303 (1962).

Bassel, R. H., G. R. Satchler, D. K. McDaniels, and D. L. Hendrie, "Alpha-Gamma Angular Correlations and the Distorted-Waves Theory," *Phys. Letters* **1**, 295 (1962).

Bassel, R. H., G. R. Satchler, R. M. Drisko, and E. Rost, "Analysis of the Inelastic Scattering of Alpha Particles. I," *Phys. Rev.* **128**, 2693 (1962).

Boom, R. W., and R. S. Livingston, "Superconducting Solenoids," *IRE Proc.* **50**, 274-85 (1962).

Boom, R. W., K. S. Toth, and A. Zucker, "Radiation Survey at the LRL 184-Inch Cyclotron," *Nucl. Instr. Methods* **18-19**, 472 (1962).

Cohen, B. L., "Evaporation Model of Nuclear Reactions," *Encyclopaedic Dictionary of Physics* **5**, 94-95 (1962).

Drisko, R. M., R. H. Bassel, and G. R. Satchler, "Distorted-Waves Analysis of Quasi-Elastic (p,n) and (He^3,t) Reactions," *Phys. Letters* **2**, 318 (1962).

Fulmer, C. B., "Elastic Scattering of Protons by Single Isotopes," *Phys. Rev.* **125**, 631-38 (1962).

Gleason, G. I., I. J. Gruverman, and J. L. Need, "Practical Production Yields of Radionuclides with 17- and 21-Mev Protons," *Intern. J. Appl. Radiation Isotopes* **13**, 223-28 (1962).

- Goodman, C. D., J. B. Ball, and C. B. Fulmer, "Single Particle Neutron Bound States in Iron Isotopes and in Cobalt Studied with (p,d) Reactions," *Phys. Rev.* **127**, 574-82 (1962).
- Goodman, C. D., and J. B. Ball, "A System for Detecting and Processing Energy Spectra for Several Types of Charged Particles Simultaneously," pp 163-67 in *Proceedings of the Symposium on Nuclear Instruments, Harwell, 1961*, ed. by J. B. Birks, Academic Press, New York, 1962.
- Goodman, C. D., G. D. O'Kelley, and D. A. Bromley, "A 20,000-Channel Pulse-Height Analyzer with Two Coordinate Address," pp 197-200 in *Proceedings of the Symposium on Nuclear Instruments, Harwell, 1961*, ed. by J. B. Birks, Academic Press, New York, 1962.
- Halbert, M. L., "Surface-Barrier Counters for Nuclear Reaction Studies," pp 403-13 in *Proceedings of the Nuclear Electronics Conference, Belgrade, 1961*, vol 1, International Atomic Energy Agency, Vienna, 1962.
- Harmatz, B., T. H. Handley, and J. W. Mihelich, "Properties of Nuclear Levels in a Number of Odd-A Nuclei ($151 \leq A \leq 191$)," *Phys. Rev.* **128**, 1186-1230 (1962).
- Howard, F. T., "Catalogue of Isochronous Cyclotrons," *Nucl. Instr. Methods* **18-19**, 125 (1962).
- Hudson, E. D., R. S. Lord, M. B. Marshall, W. R. Smith, and E. G. Richardson, Jr., "Achievement and Measurement of the ORIC Magnetic Field," *Nucl. Instr. Methods* **18-19**, 159 (1962).
- Jones, R. J., "Remarks on Tune-Up of Analogue II," *Nucl. Instr. Methods* **18-19**, 469 (1962).
- Jones, R. J., E. D. Hudson, R. S. Livingston, R. S. Lord, M. B. Marshall, W. R. Smith, W. H. White, Jr., and R. E. Worsham, "Unique Features in the Oak Ridge Isochronous Cyclotron," *Nucl. Instr. Methods* **18-19**, 46 (1962).
- Linder, B., and A. Zucker, "Radiative Capture of Nitrogen-14 on Phosphorus-31," *Phys. Rev.* **127**, 1280-83 (1962).
- Livingston, R. S., E. D. Hudson, R. J. Jones, R. S. Lord, J. E. Mann, J. A. Martin, F. M. Russell, N. F. Ziegler, and A. Zucker, "Concepts of an Mc^2 Cyclotron," *Nucl. Instr. Methods* **18-19**, 438 (1962).
- Martin, J. A., and J. E. Mann, "Beam Characteristics in Cyclotron Analogue II," *Nucl. Instr. Methods* **18-19**, 461 (1962).
- Martin, J. A., J. E. Mann, and R. S. Livingston, "Initial Performance of an Eight-Sector Electron Cyclotron," pp 355-69 in *International Conference on High Energy Accelerators, Upton, New York, 1961*, ed. by M. H. Blewett, Division of Technical Information, AEC, Washington.
- Newman, E., "Proton Transfers in the Nitrogen-Boron System at 27.5 Mev," *Phys. Rev.* **125**, 600-605 (1962).
- Rost, E., "Analysis of Inelastic Scattering of Alpha Particles-II+," *Phys. Rev.* **128**, 2708 (1962).
- Toth, K. S., "Angular Distribution and Ranges of N^{13} Particles Resulting from 27.5-Mev N^{14} Ions on Mg^{24} ," *Phys. Rev.* **126**, 1489-92 (1962).
- White, W. H. Jr., "Magnet Regulators for ORIC," *Nucl. Instr. Methods* **18-19**, 170 (1962).
- White, W. H., Jr., B. Duelli, and R. J. Jones, "Beam-Phase Measurement Studies," *Nucl. Instr. Methods* **18-19**, 601 (1962).
- Ziegler, N. F., "A High-Voltage Regulator for the ORNL 86-Inch Cyclotron," *Nucl. Instr. Methods* **18-19**, 197 (1962).

Advisory Committee

The Annual Information Meeting of the Electronuclear Division was held jointly with the Physics Division on August 21–22, 1962. The Advisory Committee selected to review these research programs was as follows:

Prof. H. Feshbach	Massachusetts Institute of Technology Cambridge
Prof. W. A. Fowler	California Institute of Technology Pasadena
Dr. M. Goldhaber	Brookhaven National Laboratory Upton, N.Y.
Prof. L. J. Rainwater	Columbia University New York
Prof. J. A. Wheeler	Princeton University Princeton, N.J.

Research Consultants

University scientists serving, under subcontract, as consultants to the Division include the following:

C. J. Bergeron	Louisiana State University, New Orleans
H. F. Bowsher	University of Michigan, Ann Arbor
G. Breit	Yale University, New Haven, Conn.
D. A. Bromley	Yale University, New Haven, Conn.
B. L. Cohen	University of Pittsburgh, Pittsburgh, Pa.
R. M. Drisko	University of Pittsburgh, Pittsburgh, Pa.
Morton Gordon	Michigan State University, East Lansing
Edith C. Halbert	
M. S. Livingston	Massachusetts Institute of Technology, Cambridge
J. W. Mihelich	University of Notre Dame, Notre Dame, Ind.
H. M. Moseley	Texas Christian University, Fort Worth
J. R. Richardson	University of California, Los Angeles
H. K. Ticho	University of California, Los Angeles
A. Timnick	Michigan State University, East Lansing
L. D. Wyly, Jr.	Georgia Institute of Technology, Atlanta

Miscellaneous Activities of the Electronuclear Division

The Division continues to engage in a variety of educational activities as part of its research function and as a responsibility to the scientific community. Included in these are the employment and training of undergraduate and graduate students, lectures at various universities, seminars, and related matters.

THESIS RESEARCH

During the past year two PhD candidates completed their thesis research in the Electronuclear Division and were awarded their degrees. G. L. Kochanny, Jr., from Michigan State University did his research problem with the ORNL 86-Inch Cyclotron nuclear physics group. J. W. Wachter, on leave from Union Carbide Nuclear Company (Y-12 Plant), completed his research with the heavy-particle physics group in connection with his studies at the University of Tennessee. Also, M. E. Wetzen and C. B. Hose, both candidates for the master's degree from the University of Tennessee, have worked with the heavy-particle physics group.

OAK RIDGE GRADUATE FELLOWSHIP

R. F. Sweet, doctoral candidate from the University of Texas, joined the Division in October as an Oak Ridge Graduate Fellow. He is working with the proton physics group on research related to his thesis.

COOPERATIVE RESEARCH PROJECT

A cooperative program of the Electronuclear Division and Vanderbilt University in the measurement of properties of superconductors at high magnetic fields was continued through 1962. Both the pulsed-magnet facility at Vanderbilt and the high-field solenoid at ORNL were used for these measurements.

RESEARCH PARTICIPANTS

Several faculty members from southern universities were at the Laboratory as research participants during the summer of 1962: H. F. Bowsher from the University of Tennessee and F. E. Durham from Tulane University participated in the heavy-particle physics program. D. H. Rester of Tulane University and J. C. Stoltzfus of Virginia Polytechnic Institute were with the 86-Inch Cyclotron proton physics group. T. I. Hicks from Howard College worked with the ORIC magnet group. C. J. Bergeron from Louisiana State University at New Orleans and R. J. Deck from the Baton Rouge Campus were active in the superconductivity studies.

VISITING SCIENTISTS

Two visiting scientists have been on assignments with the isochronous cyclotron group. Bruno Duelli completed his assignment and returned to Kernforschungszentrum, Zyklotron Laboratorium, Karlsruhe, Germany. F. M. Russell received a six-month extension from the National Institute for Research in Nuclear Science, Rutherford High Energy Laboratory, Chilton, England. In an exchange agreement, R. E. Worsham is on assignment to the Rutherford Laboratory.

SUMMER EMPLOYEES

University students employed for the three summer months included T. H. Boyer, from Yale, and M. P. Fricke, who worked with the high-energy accelerator group; J. C. Huber, from the University of Missouri, and J. D. Jones, from Mississippi State University, assigned to the ORIC group; and C. E. Johnson, from Yale, who worked with the heavy-particle physics group.

CO-OP STUDENTS

The Division continues to participate in cooperative work-study programs with educational institutions. J. H. Hemman and his alternate, B. W. Jaeger, both from the University of Missouri School of Mines and Metallurgy, completed their work with the ORIC group. R. W. Rutkowski and his alternate, S. Cushner, both from Drexel Institute of Technology, continued their work with the high-energy electro-nuclear machines group. A new alternating pair from Drexel, T. P. McBride and J. Farrington, began their assignments with the ORIC group.

INVITATION LECTURES

R. H. Bassel	Los Alamos Scientific Laboratory, June 14, 1962
University of Kentucky, December 14, 1962
"Inelastic Scattering of Alpha Particles"
R. W. Boom	Argonne Users Group, May 11, 1962
Institut fur Strahlen-und Kernphysik der Universitat,
Bonn, Germany, July 23, 1962
"Superconducting Magnets"
	Centre d'Etudes Nucleaire, Saclay, France, July 12, 1962
"ORNL Cyclotron Program and Superconducting Magnets"
	Federal Institute of Technology (ETH), Zurich, July 20, 1962
"Superconductivity Tests in External Fields and Magnet
Design Problems"
	Massachusetts Institute of Technology, December 3, 1962
"ORNL Magnet Program"
	Louisiana State University, December 8, 1962
"Superconducting Solenoids and Materials"

- C. D. Goodman Georgia Institute of Technology, March 7, 1962
 University of Virginia, January 9, 1962
 "Studies of Nuclear Structure with Direct Interaction
 Proton Reactions"
- Nobel Institute, Stockholm, Sweden, August 18, 1962
 "Nuclear Structure Studies with 22-Mev Protons"
- E. E. Gross Louisiana State University, May 3, 1962
 "Nuclear Calculations for the Nuclear Ship 'Savannah' "
- M. L. Halbert Gordon Research Conference, Nuclear Chemistry,
 New London, N.H., June 28, 1962
 "Angular Momentum Effects in Compound Nucleus
 Reactions Induced by Heavy Ions"
- J. E. Mann Vanderbilt University, April 19, 1962
 "Necessity for Graphics in Design and Building of
 Electromechanical Components and Devices"
- K. S. Toth Gordon Research Conference, Nuclear Chemistry,
 New London, N.H., June 28, 1962
 "Recent Results in Single Nucleon Transfer Reactions"
- A. Zucker University of Groningen, Groningen, Holland,
 September 12, 1962
 "Heavy Ion Induced Nuclear Reactions"

DIVISION RESEARCH SEMINARS

The Division has sponsored regularly scheduled research seminars on timely topics of special interest to the various programs. The 1962 schedule of seminars, with E. Newman as chairman, included the following:

- February 13 F. J. Perey and Brian Buck, Neutron Physics
 Division, ORNL
 "Non-Local Optical Potentials"
- February 27 Ralph Livingston, Chemistry Division, ORNL
 "Paramagnetic Resonance Studies of
 Irradiated Solids"
- March 13 F. M. Russell, National Institute for Research
 in Nuclear Science, Rutherford High Energy
 Laboratory, Harwell, England, on assignment
 with ORNL Electronuclear Division
 "Some Topics in Accelerator Research at Harwell"
- March 20 Seldon Datz, Chemistry Division, ORNL
 "Molecular Beam Studies in Physical Chemistry"
- March 22 H. Maier-Leibnitz, director Laboratorium für
 Technische Physik der Technischen Hochschule
 München, Munich, Germany
 "Physics Research Using the Swimming Pool
 Reactor at Munich, Germany"

- April 3 W. A. Fairbank, Stanford University, Stanford, Calif.
"Macroscopic Quantization in Superconductors and Liquid Helium"
- May 3 H. Bruckmann, Nuclear Physics Institute,
University of Bonn, Germany
"Research Program and Cyclotron Developments
at the Nuclear Physics Institute, University of
Bonn, Germany"
- May 8 John Landry, Chemical Technology Division, ORNL
"Project Plowshare – Peaceful Uses of Nuclear
Energy"
- May 15 K. O. H. Ziock, Yale University, New Haven Conn.
"Muonium"
- May 29 J. R. Richardson, University of California, Los Angeles
"Some Recent Operating Results with the UCLA
50-Mev Cyclotron"
- June 5 Herman Postma, Thermonuclear Division, ORNL
"Recent Experiments on DCX-1"
- June 12 C. Hwang, University of Minnesota, Minneapolis
"Proton Polarization Experiments at Intermediate
Energies"
- July 3 J. A. Martin, Electronuclear Division, ORNL
"Beam Characteristics in Cyclotron Analogue II"
- July 10 L. N. Blumberg, Electronuclear Division, ORNL
"Fission Fragment Angular Distributions"
- July 24 D. C. Peaslee, Australian National University, Canberra
"Nuclear E1 Peak Splitting"
- July 30 K. H. Bhatt, University of Chicago
"Single Particle Nilsson Model for Odd-A Nuclei in
the $1d\ 2s$ Shell"
- September 4 H. K. Ticho, University of California, Los Angeles
"Strange Particle Resonances"
- October 16 D. A. Bromley, Yale University, New Haven, Conn.
"Reaction Studies with the Yale LINAC"
- December 11 C. D. Goodman, Electronuclear Division, ORNL
"Comments on Data Handling for Nuclear Reaction
Experiments and the Use of the 20,000-Channel
Multiparameter Analyzer"
- December 18 C. J. Bergeron, Louisiana State University,
New Orleans
"Longitudinal and Transverse Critical I-H
Characteristics for the Superconductor
Nb-Zr"

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