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ELECTRONUCLEAR RESEARCH DIVISION
ANNUAL PROGRESS REPORT
FOR PERIOD ENDING JANUARY 16, 1961

OAK RIDGE NATIONAL LABORATORY
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**ELECTRONUCLEAR RESEARCH DIVISION
ANNUAL PROGRESS REPORT
For Period Ending January 16, 1961**

Robert S. Livingston, Director
Alexander Zucker, Associate Director

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OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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ELECTRONUCLEAR RESEARCH DIVISION ANNUAL PROGRESS REPORT

SUMMARY

Research with 28-Mev N^{3+} ions from the ORNL 63-Inch Cyclotron has included the studies of elastic and inelastic scattering, of angular distributions from transfer reactions, and of nuclear reactions resulting in the evaporation of alpha particles and protons. The research program associated with the 22-Mev protons from the ORNL 86-Inch Cyclotron includes studies of bound states of neutrons, the investigation of energy levels in neutron-deficient rare-earth nuclei, and the production of neutron-deficient radioisotopes. Theoretical studies are being made for the interpretation of both proton-induced and nitrogen-induced reactions with distorted-wave Born approximation calculations and with the optical model.

Fabrication and assembly of Cyclotron Analogue II are nearing completion. This eight-sector electron cyclotron will be used to investigate problems anticipated in designing a proposed 850-Mev AVF cyclotron.

The building for the Oak Ridge Isochronous Cyclotron was completed. This AVF cyclotron is a variable-energy machine designed to accelerate protons up to 75 Mev and heavy particles to over 100 Mev. The final design work is well advanced; the major heavy components have been fabricated and are being installed.

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1. HEAVY-PARTICLE PHYSICS

A. Zucker M. L. Halbert C. E. Hunting E. Newman K. S. Toth

Heavy-ion physics research in the past year has continued in three principal directions: (1) study of elastic and inelastic scattering, (2) investigation of transfer reaction angular distributions both with counters and recoil techniques, and (3) experiments concerning the evaporation of alpha particles and protons from nitrogen-induced reactions. The advent of silicon surface-barrier counters has made possible entirely new kinds of experiments in this field. These counters are being used in a coincidence arrangement to detect and identify both particles in a scattering or transfer event; they are being used as the E counter in a $(dE/dx, E)$ telescope which separates species of heavy ions; and, finally, thick barrier counters are now used to measure energy spectra of evaporated alpha particles.

SCATTERING

N^{14} - Mg^{24} Elastic Scattering

The systematic study of elastic scattering was continued; measurements are now complete on the differential cross section of N^{14} scattered by Mg^{24} at 28.2 Mev mean energy in the target, from 30 to 118° in the c.m. system.

The target was isotopically enriched metallic magnesium (99.7% Mg^{24}) evaporated from the oxide in a tantalum boat onto a glass plate. The glass plate had previously been coated with an $\sim 10\text{-}\mu\text{g}/\text{cm}^2$ film of carbon, and the magnesium-carbon foil was fluted off in water. The magnesium thickness was $45\text{ }\mu\text{g}/\text{cm}^2$, as determined by weighing and by measuring the energy loss of nitrogen ions in the foil.

The elastically scattered nitrogen ions and the recoil magnesium ions were counted separately in silicon surface-barrier counters, in coincidence. By setting the angles of the two counters to accept only elastic coincidences the events of interest could be distinguished from transfer reactions, inelastic scattering, and scattering from carbon in the target.

The differential cross section is shown as $\sigma/\sigma_{\text{Coul}}$ in Fig. 1.1. The solid line is the result of a Blair calculation for which the interaction distance $R = 7.94$ fermis. The dashed line represents a rainbow scattering calculation with $R = 8.3$ fermis and $\Delta R = 1.1$ fermis. It can be seen that the nuclear radii obtained from the two theories differ by about 5%. The rainbow fit extending over about 30° is reasonably good and gives a rather large value for $r_0 = 1.56$ fermis and a nuclear surface thickness of 1.1 fermis compared with 0.84 fermi obtained from N^{14} - Al^{27} elastic scattering.

The large radius of Mg^{24} may be associated with its deformation, and in fact is just sufficient to explain a discrepancy in transfer-reaction systematics noted several years ago. When

the function of $E^* = E_{cm} - E_{Barr} + Q$ is plotted most of the cross sections fall on one curve. Magnesium-24 is an exception if $r_0 = 1.50$ fermis is used to calculate E_{Barr} from

$$E_{Barr} = \frac{Z_1 Z_2 e^2}{r_0 (A_1^{1/3} + A_2^{1/3})}.$$

If $r_0 = 1.56$ fermis is used, Mg^{24} falls with the other magnesium isotopes and indeed with almost all targets investigated.

Fig. 1.1. The Ratio of the Elastic to the Coulomb Cross Section for N^{14} - Mg^{24} Scattering. The points are experimental results, the solid line is a Blair model calculation with $l_{max} = 8$, and the dashed line a rainbow model calculation with $\theta_r = 87^\circ$ and $\Delta R = 1.1$ fermis.

Inelastic Scattering of N^{14} by C^{12}

The inelastic scattering of N^{14} by carbon was measured at 27.3 Mev with two silicon surface-barrier counters in coincidence, one detecting the scattered N^{14} and the other the recoil carbon. With the good energy resolution of the counters and the measured angle of emission of each particle it is possible to distinguish between scattering events involving different closely lying excited states.

The most prominent scattering event at all angles was that in which C^{12} is raised to its first excited state (4.43 Mev) and the N^{14} is left in its ground state. Figure 1.2 gives the

cross section for this process. For comparison, the elastic cross section¹ at the same energy is also shown. Perhaps the most notable feature of the inelastic cross section is its relative lack of structure, in marked contrast to the elastic.

Coulomb excitation does not play a significant role in this transition. With the measured lifetime of the 4.43-Mev state² used in determining $B(E2)$, the predicted cross section is about 15 times smaller than the experimental one.

It is interesting that the probability for exciting this state in carbon by other medium-energy projectiles³⁻⁶ is an order of magnitude greater, as shown in Fig. 1.3. A satisfactory explanation of the wide gap between the two sets of cross sections has not yet been given, but the following qualitative picture may be enlightening. The chance for excitation is probably larger for close collisions than for distant ones. Simple projectiles can approach the C^{12} nucleus closely, excite it, and then successfully escape, but if the N^{14} passed close to the C^{12} it would be unlikely to escape.

Scattering to the 3.95-Mev state in N^{14} with the C^{12} left in its ground state occurs with much smaller probability. The cross section for this process is only about 15% of that for the $Q \approx -4.43$ Mev scattering. This may be connected with the single-particle nature of the 3.95-Mev state as compared with the collective properties of the 4.43-Mev level. The value of $B(E2)$ for the latter state calculated from the measured lifetime² is about seven times greater than the single-particle estimate based on the root mean square charge radius from electron scattering by carbon;⁷ the cross sections for exciting the two states similarly differ by a factor of 7. It may be noted in

Fig. 1.2. Differential Cross Section (Center-of-Mass System) for Inelastic Scattering of 27.3-Mev N^{14} by C^{12} , Exciting the C^{12} to Its 4.43-Mev Level and Leaving the N^{14} in Its Ground State. The elastic scattering cross section¹ is also shown.

¹M. L. Halbert, C. E. Hunting, and A. Zucker, *Phys. Rev.* 117, 1545 (1960).

²V. K. Rasmussen, F. R. Metzger, and C. P. Swann, *Phys. Rev.* 110, 154 (1958).

³J. D. Anderson *et al.*, *Phys. Rev.* 111, 572 (1958).

⁴R. W. Peelle, *Phys. Rev.* 105, 1311 (1957).

⁵R. G. Freemantle, W. M. Gibson, and J. Rotblat, *Phil. Mag.* 45, 1200 (1954).

⁶A. I. Yavin and G. W. Farwell, *Nuclear Phys.* 12, 1 (1959).

⁷H. Ehrenburg *et al.*, *Phys. Rev.* 113, 666 (1959).

passing that the same cross-section ratio has been found for the inelastic scattering of 9.5-Mev protons by carbon⁸ and nitrogen.⁹

Scattering to the 4.95- and 5.10-Mev states of N^{14} , with the C^{12} left in its ground state, was also observed. The two events could not be resolved; their combined cross section was about 25% as great as for the 4.43-Mev excitation. This again is consistent with the single-particle nature of these states.

A search was made for scattering to the $T = 1$, 2.31-Mev state of N^{14} (again with the carbon in its ground state). This process was not observed – the differential cross section is no more than $5 \mu\text{b/sr}$ between 40 and 140° c.m. Within the sensitivity of this experiment the isotopic-spin conservation rule is not violated.

TRANSFER REACTIONS

The transfer of a single nucleon between two nuclear surfaces involves a mechanism from which information on the wave function of the transferred nucleon may be inferred. In the semi-classical theoretical treatment of Breit and Ebel¹⁰ the trajectories followed by the incident and scattered nuclei are assumed to be classical Rutherford orbits, while the motion of the transferred nucleon is treated quantum mechanically. As these authors point out, the tunneling of the nucleon between the nuclear surfaces at low bombarding energies depends on the reduced widths of the bound-state nucleons. The nuclear parameters may be more readily deduced from reactions proceeding between discrete states. Previous investigations have summed contributions from an unknown number of individual levels. In the reactions described below the transfers involving only the ground states of the product nuclei are distinguished from all others.

The $B^{10}(N^{14}, O^{15})Be^9$ Proton-Transfer Reaction

This reaction leading to the ground states of both residual nuclei was investigated. The differential cross section was measured for center of mass angles from 20 to 156° . The cross section rises from a value of $\sim 2 \text{ mb/sr}$ at 20° to a maximum of $\sim 8 \text{ mb/sr}$ at an angle of 30° . It then drops smoothly to a value of $\sim 1 \text{ mb/sr}$ at 45° and continues to fall. Upper limits of 0.05 mb/sr

Fig. 1.3. Comparison of Cross Sections for Excitation of the 4.43-Mev Level in C^{12} by Various Projectiles. n , 14-Mev neutrons;³ p , 19.4-Mev protons;⁴ d , 19.1-Mev deuterons;⁵ α , 41-Mev alphas;⁶ N^{14} , 27.3-Mev N^{14} (present results).

⁸W. E. Burcham *et al.*, *Phys. Rev.* **92**, 1266 (1953).

⁹R. G. Freemantle, D. J. Prowse, and J. Rotblat, *Phys. Rev.* **96**, 1268 (1954).

¹⁰G. Breit and M. E. Ebel, *Phys. Rev.* **103**, 679 (1956); **104**, 1030 (1956).

are placed on measurements made at angles greater than 90° . The total cross section for the reaction is about 4 mb. The incident N^{14} energy was 27.9 Mev and the Q value +0.77 Mev.

A self-supporting B^{10} film of approximately $130 \mu\text{g}/\text{cm}^2$ was used as a target. This film was prepared by vacuum evaporation of enriched B^{10} from a carbon boat. Measurements indicated the target to be about 600 kev thick. During the experiment small amounts of carbon, oxygen, and silicon contaminants were noted in the target.

The detectors consisted of a pair of silicon-diode barrier counters. One counter detected O^{15} nuclei while the other detected Be^9 recoils. By placing these counters in correct kinematic relationship to each other it was possible to gate a 256-channel analyzer¹¹ so as to suppress to a tolerable level the unwanted events from the many other possible reactions. For example, the elastic scattering cross section at $\theta_{c.m.} = 30^\circ$ is about 10^3 times that of the transfer reaction, while the energy difference between the outgoing products is only about 500 kev. Thus, without the coincidence detection scheme, the transfer would remain buried under the tail of the elastic peak. In the region of 60° the angular difference between the elastic and transfer recoils becomes smaller than the angular resolution of the recoil counter, and the desired peak is masked.

Figure 1.4 is a plot of $d\sigma/dR_{\min}$ vs $R_{\min}$ for this reaction. Open circles represent the upper limits placed on the cross section beyond 90° . $R_{\min}$ is the classical distance of closest approach for a particle following a Rutherford scattering trajectory and $d\sigma/dR_{\min}$ is related to the differential cross section by

$$\frac{d\sigma}{dR_{\min}} = - \frac{16\pi E_{c.m.}}{Z_1 Z_2 e^2} \sin^3 \frac{\theta}{2} \frac{d\sigma}{d\Omega}$$

From this method of presenting the data it is evident that a maximum in the cross section is obtained when the centers of the nuclei are separated by a distance of 10 fermis. The value of r_0 obtained is 2.19 fermis. The solid curve is calculated from tunneling theory¹⁰ and has been normalized to the experimental data.

The $N^{14}(N^{14}, N^{13})N^{15}$ Neutron-Transfer Reaction

This reaction is quite distinctive in that: (1) N^{13} excited states are unstable with respect to proton emission to C^{12} , so that detected N^{13} nuclei are necessarily found in their ground states, and (2) the first excited state in N^{15} occurs at 5.28 Mev. Thus, N^{13} nuclei resulting from transfers to the N^{15} ground state (ground-state transfers) are at least 5 Mev more energetic than those leaving N^{15} recoils in excited states (excited-state transfers). The large energy gap makes it possible to distinguish the two sets of N^{13} particles.

¹¹M. L. Halbert and A. Zucker, *Phys. Rev.* 115, 1635 (1959).

Fig. 1.4. The Differential Cross Section $d\sigma/dR_{\min}$ Plotted vs $R_{\min}$. The curve is calculated from tunneling theory and is normalized to the experimental data. The open circles are upper limits of the cross section.

Nitrogen-13 nuclei emitted in the reaction were stopped in circular strips of aluminum foil placed at known distances from the target. From kinematics N^{13} energies at various angles were calculated for transfers leaving N^{15} recoils in their (1) ground state and (2) first excited state. To determine the angular distribution for N^{13} nuclei resulting from ground-state transfers, aluminum absorber foils of sufficient thickness to stop undesired N^{13} particles were placed in front of the catcher foils. After 20-min bombardments the catchers were separated from absorbers and were counted in shielded, calibrated Geiger counters. The amount of N^{13} present in each catcher was found by resolving the 10-min N^{13} half-life from the gross decay curve.

Figure 1.5 shows the N^{13} angular distribution for ground-state transfers obtained at incident N^{14} energies of 28 and 24 Mev. The ground-state transfer cross section decreases by a factor of ~ 2.3 as the bombarding energy is lowered from 28 to 24 Mev. The inset in Fig. 1.5 shows

the excitation function obtained for the same reaction by Reynolds and Zucker.¹² Their data show the total cross section for the reaction to remain fairly constant for incident energies between 19 and 27 Mev. To reconcile the two sets of data it was postulated that as the energy is lowered, transfers to excited states become more prevalent. To test this possibility the ranges of the observed N^{13} particles were determined at three bombarding energies, 28, 24, and 19.8 Mev. Range curves were obtained by measuring the amount of N^{13} activity as a function of the quantity of absorber placed before the catcher.

The experimental range curves revealed that there are, indeed, two sets of N^{13} particles, one possessing a range corresponding to ground-state transfers and the other with a range predicted for transfers leaving the N^{15} in its first or second excited state. The two excited states are very close together in energy, 5.28 and 5.31 Mev, and it cannot be hoped that transfers leading to these states can be distinguished. The range curves showed no additional activity, even when the amount of absorber was lowered to include N^{15} states up to 9 Mev in excitation. This information leads one to assume that only the first and/or the second excited states in N^{15} contribute significantly to the transfer cross section. The curves show that N^{13} particles due to ground-state transfers did, indeed, decrease in abundance when the bombarding energy was lowered from 28.0 to 24.0 Mev. At 19.8 Mev incident N^{14} energy no ground-state transfer N^{13} nuclei were observed. Finally, the total N^{13} activity decreased only slightly as the bombarding energy was lowered from 28.0 to 24.0 and to 19.8 Mev, in agreement with the results of Reynolds and Zucker.

Figure 1.6 shows the excited-state distributions at 24.0 and 19.8 Mev deduced from the range curves discussed above. The ground-state distribution at 24.0 Mev is included for comparison. The excited-state distributions clearly peak at larger angles than do the ground-state transfer distributions.

The distributions were replotted as $d\sigma/dR_{\min}$ vs $R_{\min}$ [see discussion in the section on the reaction $B^{10}(N^{14}, O^{15})Be^9$]. The ground-state transfer distribution obtained at a bombarding energy of 28.0 Mev was found to peak at an $R_{\min}$ of 10.5 fermis, yielding an $r_0 = 2.2$ fermis. This value of r_0 is in good agreement with that obtained for ground-state transfers at the same

Fig. 1.5. Angular Distributions at Bombarding Energies of 28.0 and 24.0 Mev for N^{13} Particles Resulting from Ground-State Transfers. The inset shows the excitation function obtained by Reynolds and Zucker for the same reaction.

¹²H. L. Reynolds and A. Zucker, *Phys. Rev.* 101, 166 (1956).

incident N^{14} energy for the $B^{10}(N^{14}, O^{15})Be^9$ reaction discussed in the previous section. Excited-state distribution data are not complete enough to observe a real maximum when plotted as $d\sigma/dR_{min}$ vs R_{min} . These distributions do seem to turn over at an R_{min} of ~ 8 fermis or an $r_0 \sim 1.65$ fermis. It is doubtful that a meaningful correlation can be made, however, between the angle at which the differential cross section peaks and the distance of closest approach for excited-state transfers where Q for the reaction is -5.00 Mev compared with an $E_{c.m.}$ of 12 Mev.

Fig. 1.6. Angular Distributions at Bombarding Energies of 24.0 and 19.8 Mev for N^{13} Nuclei Resulting from Transfers to the First and/or Second Excited States in N^{15} . The ground-state transfer distribution at 24.0 is included for comparison.

LIGHT PARTICLES FROM NITROGEN-INDUCED REACTIONS

The experimental equipment and procedure for obtaining energy spectra of light particles from reactions induced in F^{19} targets by approximately 27.4-Mev N^{14} ions were described in a previous progress report.¹³ This work was continued with the measurement of proton energy spectra from the bombardment of F^{19} with N^{14} ions at 21.4 and 27.4 Mev. Proton spectra were obtained at laboratory angles of 20, 30, 60, 75, 90, 105, 120, and 140°. Additional spectra at the higher bombarding energy were taken at 0, 5, and 10°.

The observed proton spectra were converted into the center-of-mass system of the colliding N^{14} and F^{19} nuclei by means of computer codes.¹⁴ From these spectra differential cross sections in the center-of-mass system were obtained for protons of fixed kinetic energy.

Reactions induced by heavy ions in which most of the nuclear matter fuses together and in which de-excitation takes place by the emission of light particles ($1 \leq A \leq 4$) and gamma rays have been interpreted largely in terms of the statistical model of compound nucleus processes.^{15,16} Within the framework of that model all the observed spectra have been fitted with the predictions of the simple exponential level density $\exp(E^*/T)$,¹⁷ where E^* is the excitation energy of the residual nucleus of the reaction $F^{19}(N^{14}, p)P^{32}$. Figure 1.7 shows such fits as straight lines, while Fig. 1.8 shows the parameter T as a function of angle and energy; the shape of the spectrum observed at a given angle displays no marked dependence upon bombarding energy.

¹³Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047, p 5.

¹⁴C. D. Goodman and B. D. Williams, *Nuclear Data Processing on an IBM-704 Computer with the CONDAC Program*, ORNL-2925 (May 1960).

¹⁵T. Ericson, p 697 in *Proceedings of the International Conference on Nuclear Structure*, University of Toronto Press, Toronto, Canada, 1960.

¹⁶A. Zucker, *Ann. Rev. Nuclear Sci.* 10, 27 (1960).

¹⁷T. Ericson, *Nuclear Phys.* 11, 481 (1959).

Motivation for this angular distribution work was increased by the recent extension of the well-known statistical model prediction¹⁸ of symmetry about 90° into a quantitative prediction for the entire angular distribution, on the basis of angular momentum effects in compound nucleus processes.¹⁹ The prediction for the energy and angular distribution for this case is as follows:

$$W(\theta, E_p) \propto 1 + \frac{1}{3} \beta^2 P_2(\cos \theta) + \frac{1}{35} \beta^4 P_4(\cos \theta) + \frac{5}{4158} \beta^6 P_6(\cos \theta) + \dots, \quad (1)$$

where

θ = counter angle in the center-of-mass frame of the initial collision,

$$\beta^2 = (2\sigma^2)^{-2} \frac{l(l+1)}{l(l+1)},$$

σ = characteristic spin of the residual nucleus,

l = total angular momentum of the compound system,

l = orbital angular momentum of the final system.

Fig. 1.7. Proton Energy Spectra from N^{14} on F^{19} Plotted in Such a Way That Fits to the Level Density Distribution $\exp(E^*/T)$ Appear as Straight Lines. The curves at different laboratory angles are arbitrarily displaced to avoid overlapping; each set of curves is labeled according to the laboratory bombarding energy.

Partial wave transmission coefficients from optical model calculations were used for calculating $l(l+1)$. $l(l+1)$ was calculated by interpolation from the heavy-ion, barrier-penetration calculations of Thomas²⁰ based on a square-well potential.

The combining of Eq. (1) with the predictions of the simple exponential level density formula gives

$$W'(\theta, E_p) =$$

$$(\text{const}) (\epsilon) [\sigma_c(\epsilon)] [\exp(E^*/T)] W(\theta, E_p). \quad (2)$$

¹⁸W. Hauser and H. Feshbach, *Phys. Rev.* **87**, 366 (1957).

¹⁹T. Ericson and V. Strutinski, *Nuclear Phys.* **8**, 284 (1958); **9**, 689 (1958-59).

²⁰T. D. Thomas, *Phys. Rev.* **116**, 703 (1959).

Fig. 1.8. Level Density Parameter T as a Function of Center-of-Mass Angle for N^{14} Bombarding Energies of 21.4 and 27.4 Mev.

(Here ϵ is the channel energy, including the recoil kinetic energy.) Figure 1.9 shows an approximate best fit to the 21.4-Mev results from Eq. (2), with $T = 2.14$ Mev and $\sigma = 3.18$.

On the basis of a crude classical analysis¹⁹ with Hofstadter's nuclear charge distribution²¹ the above fit is consistent with a recoil nucleus moment of inertia approximately that of the rigid body value.

For the comparison with the 27.4-Mev results appropriate values of $\overline{l(l+1)}$ and $\overline{l(l+1)}$ were calculated as above. The values of σ and T from the fit to the 21.4-Mev results were retained to provide some comparison with theoretical predictions, in spite of the lack of symmetry about 90°. Figure 1.10 shows the resulting prediction.

Fig. 1.9. Fit to the Proton Differential Cross Sections at 21.4 Mev by the Modified Ericson-Strutinski Formula of Eq. (2). Note that the parameter T fixes the normalization of the theoretical curves relative to each other.

Fig. 1.10. Fit to the Proton Differential Cross Sections at 27.4 Mev from the Same Equation and Adjustable Parameters as in Fig. 1.9, but with Angular Momentum Parameters Appropriate to This Case.

It is obvious that agreement between theory and experiment at 27.4 Mev is not nearly as good as at 21.4 Mev, due especially to the excess of protons emitted in the backward hemisphere. This effect, plus the increase of T with counter angle, suggests a direct interaction mechanism in which the observed proton comes from the F¹⁹.

There may also be complicating effects due to the "secondary" protons (those following the emission of a proton or other light particle). A statistical model calculation by Fraenkel²² predicts that essentially all of the protons in the upper three-fourths of the reported proton energy range at each bombarding energy are "primary" protons (emitted before any other particle). If secondary protons are important then the above values of σ and of the nuclear moment of inertia are upper limits, while the values of T are lower limits.

²¹R. Hofstadter, *Revs. Modern Phys.* **28**, 214 (1956).

²²Z. Fraenkel, Weizmann Institute of Science, Rehovoth, Israel, personal communication.

SURFACE-BARRIER COUNTERS

Silicon surface-barrier counters have been used routinely since October 1959 for detection of heavy ions in measurements of scattering and transfer cross sections. Experiments establishing the pulse-height response and other characteristics of the counters are described in the previous Annual Report¹³ and in the open literature.²³ In everyday use these counters, prepared by the Instrumentation and Controls Division, have proved so convenient that in our work they have completely replaced scintillation counters for heavy-ion detection. In this report we describe recent applications of these counters, including: (1) identification of heavy ions in a $(dE/dx, E)$ system and (2) spectroscopy of alpha particles up to 35 Mev from nuclear reactions; some measurements of N^{14} -induced radiation damage are also presented.

Identification of Heavy Ions

The particle identification counter, Fig. 1.11, consists of a proportional counter and a surface-barrier counter. Typically, the heavy ions give up about 2 Mev in the proportional counter and then come to rest in the surface barrier. The silicon counter is effectively inside the gas counter, but both counters work well and no interaction between them has been detected.

²³M. L. Halbert and J. L. Blankenship, *Nuclear Instr. & Methods* 8, 106 (1960).

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Fig. 1.11. Particle-Identifying Counter for Heavy Ions.

Particles enter the counter through a 0.6-mg/cm^2 nickel window and traverse about 2.5 cm of gas before they stop in the silicon. Argon with 3% CO_2 flows continuously through the counter at a rate of about $1\text{ cm}^3/\text{min}$. A manostat maintains the pressure in the counter at about 6 cm Hg. The wire, 0.001-in.-diam stainless steel, is held at 420 v with respect to the outer shell. The surface-barrier counter, made of 250-ohm-cm n -type silicon, is operated with the front surface grounded and a bias of 3 v applied to the back.

The particle separation achieved in preliminary tests when a thin target containing boron, carbon, oxygen, and silicon was bombarded with 28-Mev N^{14} ions is shown in Fig. 1.12. This is a time exposure photograph of many individual oscilloscope traces. The proportional counter pulses were applied to the vertical amplifier of the scope, and the silicon counter pulses to the horizontal amplifier; the trace was brightened for a short time during each pulse. Each dot on the photograph represents one particle. This scheme of particle separation was described previously.²⁴

Each line in Fig. 1.12 corresponds to ions of one particular Z . The four intense clusters of dots are N^{14} elastically scattered by each of the four elements in the target. The line directly below is due to carbon ions, while those above are due to oxygen, fluorine, and neon. Some sodium and magnesium ions may also be present above the neon.

A new counter has been designed to minimize dead spaces in the gas. It is hoped that even sharper separation of the different heavy ions will be possible.

Spectroscopy of Alpha Particles

In counters of high resistivity (1500 to 2300 ohm-cm) sensitive regions of about 0.6 mm are achieved by biasing at 500 to 800 v. Such counters will stop 36-Mev alpha particles. They have been found very useful for measurement of evaporation spectra of alphas from nitrogen-induced reactions. Protons are of course simultaneously detected, but the maximum energy they can give up in the counter is only 9 Mev. By reducing the bias to decrease the thickness of the sensitive region, the proton cutoff can be moved to lower energy. In this way alpha spectra from 5 to 33 Mev (the maximum alpha energy) from N^{14} on O^{16} were measured simply and rapidly at 12 angles from 0 to 160° . Analysis of these data is now in progress.

N^{14} -Induced Radiation Damage

One 1500-ohm-cm counter showed a progressive increase in reverse current and noise level while it was in use, probably because of a pinhole in a foil intended to prevent the cyclotron beam from impinging on the counter. Most of these nitrogen ions had about 4 Mev energy when they hit the counter. The deterioration was first noticed after a dose of the order of $10^8\text{ N}^{14}\text{ ions/cm}^2$ had accumulated. After the total dose had reached 10^9 or 10^{10} cm^{-2} , the noise level increased sharply and the counter became unusable. Assuming that at this point the density of radiation-induced defects had become comparable with the initial concentration of impurities, each N^{14} ion produced on the order of one to ten defects in the silicon.

²⁴C. D. Goodman and J. L. Need, *Phys. Rev.* 110, 676 (1958); C. D. Goodman, *Proceedings of the Conference on Reactions Between Complex Nuclei*, May 5-7, 1958, Gatlinburg, Tennessee, ORNL-2606, p 94.

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PHOTO 52823

Fig. 1.12. Example of Separation of Heavy Ions Achieved with the Particle-Identifying Counter. Each dot represents one particle; the ordinate is proportional to its energy loss in the gas counter and the abscissa to the energy it gave up in the silicon counter. The line with four intense clusters of dots is due to nitrogen particles. The line just below is from carbon ions, while those above are due to oxygen, fluorine, and neon.

2. PHYSICS RESEARCH WITH 22-Mev PROTONS

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The physics research program at the 86-Inch Cyclotron has evolved into three main lines of endeavor. One is a study of the bound states of neutrons as observed in pickup reactions. Another is a study of energy levels in neutron-deficient isotopes of the rare-earth region; internal conversion spectrographs are used to investigate the radioactive decay of the nuclei. Also, the high intensity of the proton beam is being evaluated for and utilized in the production of a variety of radioisotopes.

PICKUP REACTION STUDIES

Previous work at the 86-Inch Cyclotron has demonstrated that (p,d) reactions are useful for studying neutron bound states.¹ The interpretation of the deuteron spectra is discussed in the references. The investigation has been concentrated in the region of the nuclear $1f$ and $2p$ shells between $N = 20$ and $N = 40$. This stems not only from increasing theoretical interest in that region, but also from the fortunate circumstance that there are 36 stable, metallic isotopes from Ca^{40} to Zn^{70} which span the entire $1f$ and $2p$ shells. Although much remains to be done in target technology before all 36 of the targets are prepared, foils of several important isotopes were received from Argonne National Laboratory and from Los Alamos Scientific Laboratory; many more foils have been promised by the ORNL Isotopes Division.

The particle-selective counting system used in this study was improved by replacing the gas proportional counter (dE/dx counter) with a surface-barrier counter made on a 0.003-in. wafer cut from a silicon crystal.² The small size of the counter makes it possible to place it close to the scintillation counter so that particles multiply scattered in the dE/dx counter cannot be scattered out of the acceptance cone of the E counter. The fast recovery time of the silicon counter permits a higher counting rate than was possible with the gas counter. The gain stability of the silicon counter is excellent, and it is easier to use than the gas counter; it eliminates the gas system and fragile windows.

Deuteron energy spectra were measured for Fe^{54} , Fe^{56} , Fe^{57} , Fe^{58} , Co^{59} , and Ni^{64} targets. The prominent peaks in all these spectra have angular distributions characteristic of angular momentum changes of three units or one unit, as would be expected in the region of the $1f$ and $2p$ shells. The spectrum from $\text{Fe}^{54}(p,d)\text{Fe}^{53}$ shows one prominent peak at $Q = -11.2$ Mev. This is interpreted as due to the picking up of one neutron from the filled $f_{7/2}$ shell. Similar $l = 3$ peaks occur near $Q = -11$ Mev in the deuteron spectra from Fe^{56} , Fe^{57} , Fe^{58} , Co^{59} , and Ni^{64} ; these are also interpreted as due to picking up an $f_{7/2}$ neutron. The Q values for these peaks are given in

¹C. D. Goodman and J. B. Ball, *Phys. Rev.* 118, 1062 (1960); J. B. Ball and C. D. Goodman, *Phys. Rev.* 120, 488 (1960).

²The counter was obtained from the ORNL Instrumentation and Controls Division.

Table 2.1. For Fe^{56} an $l = 3$ peak appears also at $Q = -11.8$ Mev, which is weaker than the primary $f_{7/2}$ peak at -10.4 Mev. A peak at about that Q value might exist for Fe^{58} , but the uncertainty in the subtraction of background from the 43% Fe^{56} content of the Fe^{58} target makes the peak uncertain.

Table 2.1. Peaks in the (p,d) Spectra Corresponding to Momentum Transfer of Three Units

Target	$Q(p,d)$	Excitation Energy	Approximate Relative Cross Section ^a
Fe^{54}	-11.2	0	1
Fe^{56}	-10.4	1.4	1
Fe^{56}	-11.8	2.8	0.3
Fe^{57}	-7.4	2.0	<0.1
Fe^{57}	~ -9.4	4.0	~ 1 , broad or double
	~ -9.9	4.5	
Fe^{58}	-10.0	2	~ 0.7
Co^{59}	~ -11	~ 3	~ 0.6
Ni^{64}	-10.8	3.4	Not yet measured

^aTo convert the relative cross section to absolute cross section, compare with Fig. 2.1.

Table 2.2 lists the Q values for the $l = 1$ peaks. One striking feature of the data is that there are too many $l = 1$ states to be accounted for by the spherical potential shell model with no residual interactions. In particular, the existence of two well-separated $l = 1$ peaks in $\text{Fe}^{58}(p,d)$ and the absence of $l = 3$ peaks in $\text{Ni}^{64}(p,d)$ at less negative Q values than -10.8 are particularly puzzling.

The general features of all these spectra are reasonably accounted for by the Nilsson model. It is assumed that Fe^{54} is spherical, although the incomplete proton shell should have some deforming influence. The two neutrons outside the $f_{7/2}$ shell in Fe^{56} have a strongly deforming influence, and Fe^{56} is prolate. This deformation holds for Fe^{57} and Fe^{58} ; however, Co^{59} is once more spherical due to the restoring influence of the odd proton. Nickel-64 is prolate; this nuclide has eight neutrons outside the $N = 28$ shell, and in a spherical potential at least two of them would have to be in $f_{5/2}$ states. The prolate deformation, however, has the effect of increasing the binding energy of the low-spin substates relative to the high-spin substates so that all eight neutrons can be in $\frac{1}{2}$ and $\frac{3}{2}$ spin states.

The data do not necessarily require the Nilsson model in its entirety, but they suggest that the residual interactions among particles outside the closed shells can be described qualitatively by a spheroidal average potential.

Theoretical work discussed elsewhere in this report made it possible to fit the angular distributions of the deuteron peaks to distorted wave pickup calculations. Figures 2.1 and 2.2 show fits to the experimental data for the $\text{Fe}^{56}(p,d)l=3$ and $\text{Fe}^{56}(p,d)l=1$ peaks, respectively. These calculations make it possible to obtain absolute reduced width from the (p,d) data.

Table 2.2. Peaks in the (p,d) Spectra Corresponding to Momentum Transfer of One Unit

Target	$Q(p,d)$	Excitation Energy	Approximate Relative Cross Section ^a
Fe^{56}	-9.0	0	1
Fe^{56}	-9.4	0.4	0.4
Fe^{57}	-5.4	0	0.1
Fe^{57}	-6.2	0.8	0.6
Fe^{57}	(-8.3 to -8.8)	(2.9 to 3.4)	0.7, broad or double
Fe^{58}	-8	0	2.2
Fe^{58}	-9.4	1.4	0.6
Co^{59}	-8	0	2.4
Ni^{64}	-7.4	0	Not yet measured
Ni^{64}	-9.4	2	Not yet measured

^aTo convert relative cross section to absolute cross section, compare with Fig. 2.2.

Fig. 2.1. The Differential Cross Section for $\text{Fe}^{56}(p,d)\text{Fe}^{55}$ to the Excited State in Fe^{55} at 1.4 Mev. The points are experimental. The solid curve is a theoretical distorted wave calculation arbitrarily normalized to the experimental points.

Fig. 2.2. The Differential Cross Section for $\text{Fe}^{56}(p,d)\text{Fe}^{55}$ to the Ground State plus the First Excited State of Fe^{55} . The points are experimental. The solid curve is a theoretical distorted wave calculation arbitrarily normalized to the experimental points.

Since these calculations require optical model potentials for the proton-nucleus and deuteron-nucleus systems, it was felt desirable to obtain optical model parameters for the proton-nucleus system by measuring the elastic-scattering, differential cross sections and total reaction cross sections for the same targets that are used in the (p,d) work. The elastic-scattering measurements present no particular difficulty, and several angular distributions for the separated isotope targets were obtained.

A study was made of techniques for measuring total, proton-induced, reaction cross sections. The scheme adopted consists of a passing counter in front of the target and a stopping counter behind the target. A proton which does not interact with the target produces a characteristic pulse in the passing counter and a full-energy E pulse in the stopping counter. Protons which react in the target produce the characteristic dE/dx pulse with a different E pulse or with no E pulse. Since both counters have finite resolution, no combination of single-channel, pulse-height discriminators can give unambiguous results. It was found necessary to use a true, two-parameter, pulse-height recording system for the two counters in order to be able to unfold the counter resolution from the pulse-height spectra. It is also necessary to use a double passing counter with a coincidence circuit to cut down the background. A second experiment with the target in front of the passing counter is required to distinguish between reactions in the target and reactions in the stopping counter.

Transistor circuits were constructed so that the two-parameter, pulse-height recording could be done on the 400-channel analyzer in a 4×100 array similar to that used for the (p,d) work.

The study of elastic scattering from isobars, reported previously,³ was extended to Fe^{58} and Ni^{58} . The shapes of the angular distributions for 22-Mev protons are not discernibly different. The motivation of the work was to look for a dependence of the optical model potential on the nuclear symmetry parameter. The results of this search are negative, but the data will be used along with other scattering data as noted above.

NUCLEAR LEVELS IN Yb^{172}

The electron-capture decay of Lu^{172} (6.7 days) to levels in Yb^{172} has been studied with the internal conversion electron spectrograph. The lutetium activity is made in the ORNL 86-Inch Cyclotron by a $(p,2n)$ reaction on Yb^{173} . By the use of high-intensity, "mass-free" activities electroplated onto fine wires, it has been possible to catalog (Table 2.3) 95 transitions up to 2.1 Mev which are 10^{-6} times as intense as the strongest line. The possible decay scheme shown in Fig. 2.3 is based on this data and some scintillation counter measurements.⁴ The criteria employed in the construction of this scheme were transition energy fits, multipolarities, intensities (measured or deduced), internal consistency of rotational parameters, and interband and intraband branching ratios.

³Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047.

⁴R. G. Wilson and M. L. Pool, *Phys. Rev.* **118**, 1067 (1960).

Table 2.3. Conversion Electron Data for Decay of Lu^{172} (6.7 Days) $\rightarrow \text{Yb}^{172}$

Transition Energy (keV)	Intensity ^a						Assignment ^b
	K	L _I	L _{II}	L _{III}	M	N	
78.7	> 200	c	1100 ^c	1100	600	170	E2(2 ⁺ → 0 ⁺)
90.6	> 195	50	225	220	110	40	E2/M1 = 3
112.7	53	6	24	21	11	3	E2/M1 = 3.6
134.3	2.3	c	0.83 ^c	0.55	0.3		E2/M1 = 3.2
145.9 ^d	3.4	< 1.2 ^e					
155.7 ^d	1.1	0.15					
163.0	3.0	0.45					
181.4	210	c	59 ^c	46	28	8	E2(4 ⁺ → 2 ⁺)
196.7	< 1.2 ^e						
199.8	0.3						
203.3	37	c	9 ^c	6.7	4.5		E2
210.3	1.7	0.2					
228.9 ^d	4.6	e					
247.0	2.8	c	0.8 ^c	0.5			E2
264.9 ^d	1.5	0.25					
269.9	17.5	2.9			< 1.4 ^e		
279.7	4.5	1.2	e	0.4	0.33		E2(6 ⁺ → 4 ⁺)

Transition Energy (keV)	Intensity ^a		Transition Energy (keV)	Intensity ^a	
	K	L		K	L
319.0 ^d	0.9	w	416.3 ^d	0.2	
323.8	9	1.3	427.0	0.3	
329.0 ^d	< 1.4 ^e	0.11	432.3 ^d	0.7	
337.4	~0.2		437.3	0.6	
352.4 ^d	0.17		442.6 ^d	~0.1	
358.2 ^d	0.48		482.1	0.87	e
366.3 ^d	0.22		486.0	1.05	< 0.72 ^e
372.3	7.2	1.1	490.2	3.6	< 2.4 ^e
373.3	0.5	e	512.4 ^d	0.28	
377.3 ^d	1.6	0.25	528.1	6.0	0.85
399.5	1.9	0.23	535.9	< 0.72 ^e	
410.1	4.9	0.8	540.2	< 2.4 ^e	0.25
415.2 ^d	w		550.7 ^d	0.5	w

Table 2.3 (continued)

Transition Energy (keV)	Intensity ^a		Transition Energy (keV)	Intensity ^a	
	K	L		K	L
576.4	~0.33		1194.4 ^d	w	
584.5	0.33	w	1290.2	0.03	
594.3 ^d	0.4	w	1324.4 ^d	w	
607.1 ^d	0.19		1388.7	0.05	
622.4	0.19		1399.6	w	
630.6	0.42	c	1404.1	0.048	
682.0	0.6	w	1433.8 ^d	w	
685.2 ^d	w		1441.7	0.042	
697.8	4.5	0.54	1467.6	0.04	
709.0 ^d	0.37		1471.3	0.04	
715.0 ^d	w		1480.2 ^d	w	
722.8 ^d	0.3		1490.2	0.08	
810.6	8.2	1.3	1544.5	0.07	w
816.9	0.65		1585.7	0.145	0.02
901.4	11.2	1.8	1604.2	0.025	
913.4	3.5	0.6	1623.5	0.11	<0.034 ^e
930.0	1.13	0.16	1672.0 ^d	<0.034 ^e	
968.8 ^d	w		1726.0	0.04	
1004.4	1.05	0.15	1769.0 ^d	w	
1023.7	0.46	0.08	1786.9 ^d	w	
1042.4 ^d	0.12		1814.0	~0.013	
1082.3 ^d	0.24	w	1851.3 ^d	w	
1095.3	7.6	1.2	1869.2 ^d	0.015	
1114.2	0.41	0.07	1915.8 ^d	0.05	
1117.3	w		1995.7	~0.01	
1126.6 ^d	~0.04		2025.8 ^d	w	
1150.4 ^d	w		2083.5 ^d	~0.01	
1161.8 ^d	w				
1176.3 ^d	~0.03				
1186.0	~0.044				

^aIntensity data are normalized to 1100 units for the most prominent line. "w" indicates weak line.

^bMultipole assignments are based on K/L and L-subshell ratios.

^cConversion line is partially resolved.

^dNot assigned in decay scheme.

^eConversion line is a composite of two different lines.

Fig. 2.3. Levels in Yb^{172} Populated by Electron-Capture Decay of Lu^{172} . Rotational sequences are aligned vertically. All energy values are given in kev. Electron-capture branches to various levels are shown by dashed lines with relative intensities in per cent and $\log ft$ values underlined.

The ground-state rotational sequence closely follows the $I(I + 1)$ interval rule to $I = 6$ at 539.8 keV. The deviation of the predicted energy value for the latter level is 0.9 keV. A strongly developed rotational pattern of spin sequence $I = 3, 4, 5$, and 6 is based at 1174.0 keV. This level structure is populated by intense intraband transitions of $E2/M1 = 3$ character where $\Delta I = 1$ and of $E2$ multipolarity where $\Delta I = 2$. Intraband branching ratios of $E2$ radiation indicate that quantum number K is very likely the same value (3) as the spin of the base state. Positive parity is indicated by intensity considerations.

A weakly populated band which is based at 1467.5 keV proceeds to the ground-state ($K = 0$) sequence. If quadrupole radiation is assumed, experimental branching ratios are consistent with the premise that this may be a gamma-vibrational band. Similar energy levels in Yb^{172} via β^- decay of the presumably low-spin Tm^{172} were recently reported.⁵

Two close-lying states at 1664.3 and 1702.1 keV feed all lower levels of $I = 2, 3$, and 4. Spin 3 is postulated for both of the above states, and positive parity is indicated to maintain an intensity balance. Rotational states of spin 4 at 1750.6 and 1804.7 keV are found to de-excite to the $I = 3, 4$, and 5 levels of the 1147-keV band with a reduced gamma-ray intensity ratio close to that predicted for $K_i = K_f = 3$.

The electron-capture decay proceeds mainly to the high-spin states at 2075.0 keV ($I = 4$), 2194.2 keV ($I = 5$), and 2287.3 keV ($I = 4$). A spin of 4 is predicted for the odd-odd parent, Lu^{172} , which is consistent with $\log ft$ values of the electron-capture branches.

The moment of inertia parameter $3\hbar^2/2J$, associated with rotational spectra in Yb^{172} , follows a trend analogous to W^{182} . The inertial parameter in Yb^{172} is highest for the gamma-vibrational band (83 keV), followed by the ground-state band (79 keV), and ranges from 65 to 77 keV for those base-state bands where $I_0 \geq 3$.

APPLIED PHYSICS PROGRAM

Arrangements are made (under AEC full-cost-recovery program) for cyclotron time and service irradiations on the ORNL 86-Inch Cyclotron for other research programs of this Laboratory, for Federal agencies, and for other organizations and laboratories. Cyclotron time available for this program was increased from 28 hr out of an 80-hr week to 60 hr of a 112-hr week during the last quarter. The increase in service irradiations since the program was initiated is shown in Fig. 2.4.

Service irradiations were provided for 19 institutions, in addition to several divisions of the Laboratory, see Table 2.4. Certain commercial processors and the United Kingdom Atomic Energy Authority process and further distribute materials; for example, As^{74} is routinely supplied to some ten hospitals in the United States on a three-week schedule.

The most intense beam was 2600 μA , used during the irradiation of a solid silver target for the production of Cd^{109} . The least intense beam was a current of 0.01 μA used to simulate the radiation damage in components of a satellite transiting the Van Allen belt; this beam was monitored by observing the gamma radiation produced in the target.

⁵R. C. Helmer and S. B. Burson, *Dull. Am. Phys. Soc.* 5, 425 (1960).

Fig. 2.4. Annual Charges for Irradiation Services, ORNL 86-Inch Cyclotron.

The isotopes produced are shown in Table 2.5. The table is somewhat incomplete since processors may also remove by-product activities from the targets; for example, carrier-free Zn^{65} is obtained from the flat copper plate used as a base for many targets, and carrier-free Al^{26m} is removed from the magnesium targets used in the production of Na^{22} .

The wide variety of neutron-deficient isotopes of considerable importance in basic and applied research which are produced at high isotopic purity and with high specific activity underscores the usefulness of a high-current cyclotron. For example, As^{74} is being regularly produced in 220–240 mc quantities, and Co^{57} in curie quantities. The recent applications of the Mössbauer effect (the recoilless gamma-ray emission and absorption) to laboratory-scale investigations of the theory of relativity are made possible by the production of Co^{57} on this cyclotron. This machine is the only important source for many of the isotopes listed in Table 2.5.

In some cases the cyclotron competes, in effect, with nuclear reactors because of the higher purity of the products. For example, 7.2-yr Ba^{133} is produced in reasonable quantities (carrier-free) for gamma calibration work; the present production rate is $54 \mu\text{c/hr}$ in a capsule target. The reactor

Table 2.4. Customer Distribution for Service Irradiations, 86-Inch Cyclotron

Universities

Georgia Institute of Technology
 Ohio State University
 Pennsylvania State University
 Princeton University
 University of Chicago
 University of Notre Dame
 Vanderbilt University
 Western Reserve University

Hospitals

Argonne Cancer Hospital
 Jewish Hospital, St. Louis
 University of California Medical Center

U.S. Government Agencies

National Aeronautics and Space Administration
 McClellan Air Force Base

Oak Ridge National Laboratory

Physics Division
 Chemistry Division
 Chemical Technology Division
 Isotopes Division
 Metallurgy Division

Commercial Processors

Abbott Laboratories
 Nuclear Science and Engineering Corporation

Foreign Organizations

N.V. Philips-Duphar, Netherlands
 Saha Institute of Nuclear Physics, India
 Tata Institute of Fundamental Research, India
 United Kingdom Atomic Energy Authority, England

product Ba-133-P Process, High Specific Activity, available at $> 500 \mu\text{c}$ per gram of barium is not completely satisfactory for the 357-keV gamma line calibration, since it is far from carrier-free. Another example is the 8-day I^{131} which has diagnostic and therapeutic uses. This activity has disadvantages both in half-life and spectra when compared with the cyclotron-produced 4.5-day I^{124} and 57.4-day I^{125} . Requests for I^{124} and I^{125} , the production technology of which is being developed at the present time, exceed 150 mc.

Research in the Applied Physics program concentrates mainly on the exploitation of the unique high intensity of the 22-MeV proton beam, on development of suitable targets to withstand this beam, and on the measurement of target yields and excitation functions. Improved performance of capsule targets and of flat-plate targets was achieved by routinely x-raying them; ultrasonic testing of flat-plate targets further eliminated unwanted voids and nonbonding of surfaces. Extremely high-purity, low-cobalt briquettes used in rolling nickel foils are used as the anode for plating high-purity nickel onto copper for flat-plate targets which are suitable for Mössbauer studies. Formerly, only foil could be used; this limited the beam to $< 1 \text{ ma}$. A beam of $1400 \mu\text{a}$ has had no deleterious

effect on the new targets. Another nickel target for high-intensity beams was prepared by silver soldering a briquette of high-purity nickel in a depression in a copper plate. After irradiation the Co^{57} activity is dissolved from the face of the target; the target may be used repeatedly.

Table 2.5. Service Irradiations, ORNL 86-Inch Cyclotron

Isotope	Runs	Irradiation Time (hr)	Charges (dollars)
Be^7	3	13	1,570
Na^{22}	11	162	9,444
V^{48}	3	4	653
Mn^{52}	2	0.7	305
Fe^{55}	2	16	1,509
Co^{56}	1	1.5	219
Co^{57}	5	33	3,189
Co^{61}	9	16	936
As^{74}	20	188	15,637
Sr^{85}	3	30	2,603
$\text{Y}^{87}, \text{Y}^{88}$	1	0.4	
Y^{88}	3	5	613
Tc^{95}	2	7	594
Rh^{102}	2	4.5	567
Pd^{103}	4	15	1,374
Cd^{109}	2	8	665
$\text{I}^{124}, \text{I}^{125}, \text{I}^{126}$	1	2	253
I^{125}	3	18	1,424
Ba^{133}	1	1	
Ce^{139}	3	14	1,294
Pm^{145}	1	1	
Pm^{148}	2	4	322
Pm^{150}	1	1.5	132
Eu^{146}	1	2	240
Eu^{147}	1	0.2	88
Eu^{149}	2	2.3	346
Yb^{171}	1	1	193
Au^{195}	1	6	889
Tl^{202}	1	0.3	103
Bi^{207}	3	4.3	300
$\text{Po}^{231}(p,x)$	11	73	4,234
Space program	5	39	2,918
Total	111	674	

Work is continuing in capsule-target and window-target development. The core of a capsule target was modified to receive the target packet which is normally used in a window target; this increased the available beam from $80\ \mu\text{a}$ to $200\ \mu\text{a}$. The use of rectangular cooling channels in copper flat-plate targets increased the water flow over 50% and allows better utilization of the beam. The external beam target position was redesigned to permit faster target changes, provide better cooling, and reduce personnel exposure. Window-type targets irradiated with a degraded beam are utilized to produce Co^{57} in millicurie quantities. Instead of using only aluminum foils to degrade the beam energy, the standard practice now is to use extremely high-purity, low-cobalt nickel foils along with the aluminum foils; Co^{57} is thus produced in the foremost nickel foil at a rate of approximately 1 mc/hr. This by-product from the irradiation of various targets is stockpiled.

The effect of varying the beam distribution on the target by periodically varying the auxiliary magnetic field is being investigated. An unexplained increase of about 70% in the yield of As^{74} , as well as increases in yields in the production of V^{48} , Mn^{52} , and Sr^{85} , has been observed.

Excitation functions were obtained by activation of nickel foils, of natural isotopic abundance, with 4- to 22.3-Mev protons in the deflected beam. Nickel, cobalt, and copper were separated by ion exchange and were further purified by chemical processing. Absolute cross sections were obtained by beta and gamma counting for the reactions $\text{Ni}^{58}(p,pn)\text{Ni}^{57}$, $\text{Ni}^{58}(p,\alpha)\text{Co}^{55}$, and $\text{Ni}^{64}(p,n)\text{Cu}^{64}$. The decay was followed through seven or eight half-lives. These excitation functions are shown in Figs. 2.5, 2.6, and 2.7, respectively. It should be noted that Kaufman's values⁶ have since been revised⁷ (10% downward) and are now in good agreement.

⁶S. Kaufman, Princeton, private communication.

⁷S. Kaufman, *Phys. Rev.* 117, 1532 (1960).

Fig. 2.5. Excitation Function for the Reaction $\text{Ni}^{58}(p,pn)\text{Ni}^{57}$. The work of Cohen, Newman and Handley appears in *Phys. Rev.* 99, 723 (1955).

Fig. 2.6. Excitation Function for the Reaction $\text{Ni}^{58}(p, \alpha) \text{Co}^{55}$.

Fig. 2.7. Excitation Function for the Reaction $\text{Ni}^{64}(p, n) \text{Cu}^{64}$. The work of Tanaka and Furukawa appears in *J. Phys. Soc. Japan* 14, 1269 (1959) and the work of Blosser and Handley appears in *Phys. Rev.* 100, 1340 (1955).

3. NUCLEAR REACTION THEORY

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Studies in nuclear theory are undertaken to interpret the results obtained in experimental work with the 63-in. and 86-in. cyclotrons. Data obtained through nitrogen-induced and proton-induced reactions are analyzed in terms of the distorted-wave Born approximation and the optical model.

DISTORTED-WAVE CALCULATION (OFF-DIAGONAL REACTION PROCESSES)

It is well known that the conventional first Born (plane-wave) approximation is often capable of qualitatively explaining direct reactions. That is, the main features of an angular distribution are reproduced and some knowledge of nuclear structure can be gained. Qualitatively, this procedure is usually in error, however; furthermore, it is incapable of explaining such processes as polarization of the outgoing particles. The distorted-wave Born approximation¹⁻³ (DWBA) takes into account, in an average way, the elastic scattering of the incoming and outgoing projectiles. It includes the distortion of these waves due to reflection, refraction, and diffraction by the nucleus before (and after) the direct reaction. This would seem reasonable if the main process associated with the incoming and outgoing particles is elastic scattering. If the elastic scattering is described by a complex potential, the model allows for the absorption of the wave into off-diagonal channels.

This model, then, is capable of giving more definite information than the plane-wave theory. It has been demonstrated that, in many cases, the predicted cross section is in good quantitative agreement with experiment.⁴ There is experimental evidence for important deviations from some of the simple general predictions of the plane-wave theory, for example, the gamma correlation. The DWBA allows quantitative calculation of these deviations. Of course, there are certain reactions (as near the Coulomb barrier) where a plane-wave theory is wholly inadequate but the DWBA is quite good.

A computer code for calculating cross sections, polarizations, and angular correlations in DWBA has been written in collaboration with G. R. Satchler of the Physics Division. The following sections (1) discuss the stripping calculations in zero-range approximation, (2) give the results of some preliminary work on the inclusion of the finite range of the neutron-proton force, and (3) discuss inelastic scattering in the DWBA.

¹C. A. Levinson and M. K. Banerjee, *Ann. Phys. (N.Y.)* **2**, 471 (1957).

²W. Tobocman and M. H. Kalos, *Phys. Rev.* **97**, 132 (1955).

³W. Tobocman, *Phys. Rev.* **115**, 99 (1959).

⁴N. Austern, p 323 in *Proceedings of the International Conference on Nuclear Structure*, University of Toronto Press, Toronto, Canada.

Stripping

The calculations, at present, make use of the zero-range approximation, suggested by Tobocman,^{2,3} for stripping, (d, p) or (d, n) , and pickup, (p, d) or (n, d) , reactions. That is, the term

$$V_{np} \Phi_d(r_{np})$$

(where V_{np} is the neutron-proton interaction and Φ_d is the internal wave function of the deuteron) which appears in the matrix elements for these reactions is assumed to be of such short range that it can be approximated by a delta function:

$$V_{np} \Phi_d(r_{np}) \longrightarrow A \delta(r_{np}) .$$

Then the matrix element for $d + A \rightleftharpoons p \text{ (or } n) + B$ is

$$\sim A \left\langle \chi_{\vec{k}_f}^{(-)\dagger}(\vec{r}) \phi_l^*(r) Y_l^m(\theta, \phi) \chi_{\vec{k}_i}^{(+)}(\vec{r}) \right\rangle .$$

Here $\chi_{\vec{k}_f}^{(-)}$ and $\chi_{\vec{k}_i}^{(+)}$ are the distorted waves in final and initial channels, and $\phi_l(r)$ is the bound-

state wave function of the captured particle in the residual nucleus B, characterized by angular momentum l . The distorted waves are represented by the optical model wave functions which "best" describe the elastic scattering in initial and final channels, when this scattering information is available. The bound-state function is taken as a cut-off oscillator function joined smoothly to a Hankel function with the correct asymptotic dependence. Alternatively, this function could be described by the solution to the Schrödinger equation with a Saxon well which gives the correct eigenvalue. The calculations described here made use of the first of these alternatives for $\phi_l(r_n)$.

After the distorted waves are expanded in spherical harmonics and the angular integrals and indicated sums are done, the calculated differential cross sections are

$$\frac{d\sigma}{d\Omega}(d, p) = A^2 \frac{m_p^* m_d^*}{k_p k_d^3} \left(\frac{M_f}{M_i} \right)^2 \frac{2J_f + 1}{(2J_i + 1)(2S_n + 1)} \bar{\sigma} ,$$

$$\frac{d\sigma}{d\Omega}(p, d) = A^2 \frac{m_p^* m_d}{k_p^3 k_d} \left(\frac{M_f}{M_i} \right)^2 \frac{1}{2S_n + 1} \bar{\sigma} ,$$

where

$$\bar{\sigma} = |B_l^0|^2 + 2 \sum_{m=0}^l |B_l^m|^2$$

and the B_l^m are the complex amplitudes. The connection between experiment and theory is then

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{exp}} = \theta^2 \frac{d\sigma}{d\Omega},$$

with θ^2 the reduced width. The polarization and angular correlations are suitable combinations of the amplitudes.^{5,6}

The present computer program allows computation of cross sections and polarizations for l values from 0 to 4. Angular correlations are calculated for l values of 1 and 2. No allowance is made for spin-orbit coupling in the elastic channels. (A new code now being checked out includes this effect.) A typical calculation with 25 partial waves in the initial and final channels requires 3 min on the IBM 704 and about 1 min on the IBM 7090 computer.

A survey was undertaken to determine the effect of varying the optical model parameters on the DWBA predictions for stripping. Partial results of this survey were reported elsewhere.⁷ These calculations are very useful for extracting reduced widths from experimental data.

The results of fixing the deuteron optical model parameters and making rather large variations in the outgoing proton optical model parameters are shown in Fig. 3.1. The reaction considered is $d + \text{Ca}^{40} \rightarrow p + \text{Ca}^{41}$, $l = 1$, with a fictitious Q of 5 Mev. Figure 3.2 shows the variation of the stripping cross section where the proton parameters are fixed and the depths of the deuteron optical wells are varied. As expected, the stripping cross section is more sensitive to the deuteron parameters. Since the deuteron-nucleus radius is larger than the proton-nucleus radius, the deuteron well in effect shields the proton well. The essential feature that these curves illustrate is that the main peak, the "Butler" peak, is insensitive to large changes in the optical parameters. With reasonable parameters, enough information is calculated to allow a meaningful comparison with experiment. There remain ambiguities in the normalization of the calculated cross sections. For instance, Tobocman and Gibbs⁸ have noted that the effective neutron-proton interaction is perhaps twice as strong as the interaction needed to bind the deuteron. Whether this is real or apparent awaits further calculations. Even if the absolute normalization is inaccurate, relative reduced widths deduced from the calculations should be accurate, especially since the penetrabilities of the particles are taken into account.

The DWBA predictions were compared with experimental results, as shown previously in Figs. 2.1 and 2.2. It should be stated that no exhaustive search was made for optical model parameters. The deuteron parameters used were those that gave a reasonable fit to the elastic scattering of 11-Mev deuterons from magnesium. The proton parameters are similar to those found for elastic proton scattering, neglecting spin-orbit forces.

⁵R. Huby, M. Y. Refai, and G. R. Satchler, *Nuclear Phys.* **9**, 94 (1958).

⁶G. R. Satchler and W. Tobocman, *Phys. Rev.* **118**, 1566 (1960).

⁷R. H. Bassel, G. R. Satchler, and R. M. Drisko, *Bull. Am. Phys. Soc.* **6**, 67 (1960).

⁸W. Tobocman and W. Gibbs, *Bull. Am. Phys. Soc.* **6**, 67 (1960).

Fig. 3.1. Distorted-Wave Predictions for Stripping Angular Distributions, for One Set of Deuteron Parameters and Several Different Sets of Proton Parameters.

Fig. 3.2. Distorted-Wave Predictions for Stripping Angular Distributions, for One Set of Proton Parameters and Several Different Sets of Deuteron Parameters.

Finite Range Effects in Stripping

A procedure is being developed for taking into account the "finite" (nonzero) range of the neutron-proton interaction in deuteron stripping and pickup. The formulation is now ready for translation into a code for the IBM 7090 computer.

This finite-range study is being done in the framework of an otherwise conventional distorted-wave treatment. It seems worthwhile to look at finite-range effects this way even though the errors contributed by zero range and by other important approximations in the conventional DWBA are interdependent. It is suspected, for instance, that the zero-range approximation incorrectly enhances the importance of contributions to the stripping integral from the nuclear interior. If the introduction of finite range does produce a general suppression of these contributions, then errors in the interior wave functions become less disturbing.

The method is applicable to $l = 0$ transfer. A brief outline of the procedure, for $A(d,p)B$ reactions, is given below. (The discussion for pickup reactions, or for proton transfer, would be entirely analogous.)

The direct reaction matrix element for $A(d, p)B$ is proportional to

$$I = \int \chi_{\vec{k}_p}^{(-)\dagger}(\vec{r}_{pB}) \phi_0^*(r_{nA}) V(r_{pn}) \Phi_d(r_{pn}) \chi_{\vec{k}_d}^{(+)}(\vec{r}_{dA}) d^3\vec{r}_{pB} d^3\vec{r}_{dA}.$$

Here $\phi_0(r_{nA})$ is the ($l=0$) effective wave function of the captured neutron. A pure S state for the deuteron is assumed. The integrand of I is transformed into an explicit function of $\vec{r}_{pB}$ and $\vec{r}_{dA}$ by expanding the product $\phi_0^* V \Phi_d$ into spherical harmonics:

$$\phi_0^*(r_{nA}) V(r_{pn}) \Phi_d(r_{pn}) = \sum_{L,M} f_L(r_{pB}, r_{dA}) Y_{LM}^*(\hat{r}_{pB}) Y_{LM}(\hat{r}_{dA}).$$

The stripping code presently available already yields coefficients for spherical harmonic expansions of $\chi_{\vec{k}_p}^{(-)}$ and $\chi_{\vec{k}_d}^{(+)}$; for example,

$$\chi_{\vec{k}_p}^{(-)}(\vec{r}_{pB}) = \sum_{\lambda, \mu} R_{p\lambda}(r_{pB}) Y_{\lambda\mu}^*(\hat{r}_{pB}) Y_{\lambda\mu}(\hat{k}_p).$$

The integral I may then be written

$$I = \frac{1}{4\pi} \sum_L (2L+1) P_L(\hat{k}_p \cdot \hat{k}_d) \int_0^\infty r_{pB}^2 dr_{pB} R_{pL}^*(r_{pB}) \int_0^\infty r_{dA}^2 dr_{dA} R_{dL}(r_{dA}) f_L(r_{pB}, r_{dA}).$$

The essential difference between this sum and the analogous zero-range sum is the appearance of a *double* radial integral for each L , rather than a single radial integral. The coefficients $f_L(r_{pB}, r_{dA})$ are made tractable by choosing for $\phi_0^*(r_{nA})$ a function of harmonic oscillator form (or a sum of such functions), and for $V(r_{pn}) \Phi_d(r_{pn})$ a simple Gaussian, $\exp(-\mu r_{pn}^2)$. Then the f_L are expressible in terms of modified Bessel functions of half-integral order. Details about further approximations and other aspects of the method are given elsewhere.⁹

The proposed finite-range code will thus allow direct comparison of zero-range and finite-range calculations for $l=0$ transfer, and for a restricted choice of functions $F \equiv \phi_0^* V \Phi_d$. Sensitivity of the results to changes in F will be studied. The code will also be used to investigate the reliability of other finite-range procedures¹⁰ which are less exact in some features, but which will allow relaxation of the restrictions on F , and/or which will consume less machine time. Generalization to $l > 0$ is planned.

Inelastic Scattering

The matrix element for the inelastic scattering process

$$a + N \longrightarrow a + N^*$$

⁹E. C. Halbert, unpublished reports.

¹⁰As suggested by N. Austern, University of Pittsburgh, unpublished report.

in DWBA is written

$$\left\langle \chi_f^{(-)} \Phi_f(N^*) \mid V \mid \Phi_i(N) \chi_i^{(+)} \right\rangle = \left\langle \chi_f^{(-)\dagger}, f_l Y_l^m(\theta, \phi) \chi_i^{\dagger} \right\rangle .$$

For single-particle excitation

$$f_l(r) \sim \phi_{n_1, l_1}(r) \phi_{n_2, l_2}(r) .$$

For collective excitation, following Chase, Wilets, and Edmonds¹¹ and Rost and Austern,¹²

$$f_l(r) \sim dU/dr ,$$

where U is the optical potential which describes the elastic scattering. Provision is made in the program to include Coulomb excitation as a perturbation. As an example, for excitation to the 2^+ state in even-even nuclei,

$$f_l(r) \longrightarrow f_l(r) + (b/r^3) .$$

Following the original calculations of Rost and Austern, who assumed the interaction to be a delta function in the surface region, Rost, Austern, and Drisko¹³ made use of this program to do more detailed calculations of the inelastic scattering of alpha particles from carbon, magnesium, and argon. Using Igo's parameters¹⁴ for elastic scattering of alpha particles, they were able to ascertain and substantiate the reaction mechanism postulated by Rost and Austern – that it is a surface reaction and that the major contribution to the reaction comes from the partial waves reflected by the nuclear surface. Blair¹⁵ has also pointed out that the quantity βR_0 (β the deformation parameter) found by this calculation agrees with measurements. It is worth noting that these calculations have no adjustable parameters once the elastic scattering has been fitted.

OPTICAL MODEL STUDIES (ELASTIC SCATTERING)

Studies of heavy-ion elastic scattering were continued with the optical model. As is well known, the Blair model¹⁶ has met with some success in explaining the elastic scattering of alpha particles. Reynolds and Zucker¹⁷ have also demonstrated the applicability of the model to heavy-ion elastic scattering. It has also been demonstrated¹⁸ that in cases where the model fails its main assumption,

¹¹D. M. Chase, L. Wilets, and A. R. Edmonds, *Phys. Rev.* **110**, 1080 (1958).

¹²E. Rost and N. Austern, *Phys. Rev.* **120**, 1375 (1960).

¹³N. Austern, p 323 in *Proceedings of the International Conference on Nuclear Structure*, University of Toronto Press, Toronto, Canada.

¹⁴G. Igo, *Phys. Rev.* **115**, 1665 (1959), and references therein.

¹⁵J. S. Blair, p 824 in *Proceedings of the International Conference on Nuclear Structure*, University of Toronto Press, Toronto, Canada.

¹⁶J. S. Blair, *Phys. Rev.* **95**, 1218 (1954).

¹⁷H. L. Reynolds and A. Zucker, *Phys. Rev.* **102**, 1378 (1956).

¹⁸W. Cheston and A. E. Glassgold, *Phys. Rev.* **106**, 1215 (1957).

that the low partial waves are completely absorbed, still holds. The successful optical model calculations and the rounded Blair model calculations have shown that an important deviation from the original model is the gradual decrease to zero of the partial wave amplitude $(1 - \eta_l)$ in the scattering amplitude.

Since the optical model analysis of nitrogen scattering from beryllium shows this behavior, the integrand of the elastic scattering matrix element was calculated for those partial waves around the Blair critical l value. There is a nonnegligible contribution to the matrix element from internuclear separations which correspond to appreciable interpenetration. This suggests that the optical model analysis would be sensitive to the shape of the wells assumed. In any case, it was not possible to find a good fit to the elastic scattering of nitrogen from beryllium by using Saxon wells with the same geometrical parameters for both real and imaginary well, but a Gaussian imaginary well provides a good description for the scattering.

A comprehensive study of the optical model is now being made for nucleon elastic scattering over a wide range of energy and atomic number. This work will include studies on the dependence of the theoretical scattering on the well shapes assumed. Another study will attempt to find the systematics and invariances of the optical model.

An examination of the variations of the partial wave amplitudes with infinitesimal variations of the parameters will make it possible to expand the amplitudes in a series as a function of the parameters. Extensive preliminary hand calculations have been made from the output of the present optical model code. On the basis of these, the code was revised to permit making the meaningful comparisons on the machine. With the machine making the desired comparisons, this study can proceed much more rapidly than heretofore.

A study of the effect of the shape of the charge distribution on the elastic scattering is included in this program. Hitherto, the Coulomb potential used in the optical code described the interaction of a point particle with a square-well charge distribution. It is well known that the charge distribution found experimentally is rounded, and accordingly, the Coulomb well derived from a rounded distribution is incorporated. It was found that, for this well, low-energy proton scattering is indistinguishable from that found for a square well if appropriate radii are chosen. For example, for proton scattering from argon at 10 Mev (with the nuclear parameters unchanged) it is found that a rounded charge distribution with a radius parameter of 1.12 fermis gives the same angular distribution as a square-well distribution with a radius parameter of 1.26 fermis.

4. CYCLOTRON OPERATION

A. W. Riikola

H. L. Dickerson

C. L. Viar

Both the 86-in. and the 63-in. cyclotron have operated routinely with no major interruptions. A regulator is being installed in the high-voltage supply to the oscillator of the 86-Inch Cyclotron to provide voltage regulation to about 0.1%.

DEE-VOLTAGE REGULATOR FOR THE 86-INCH CYCLOTRON

N. F. Ziegler

Detailed measurements indicated that variations in the 86-Inch Cyclotron beam with time were quite sensitive to minor fluctuations in the power supply to the oscillator. A regulator was developed to maintain the plate voltage constant to within 0.1%. The cyclotron is scheduled to be shut down on January 16, 1961, for about one month for installation of the regulator.

A simplified circuit diagram of the regulator is shown in Fig. 4.1; stabilizing networks are omitted. Although the regulator is relatively simple, numerous modifications of the existing system were necessary to permit its installation and to protect the oscillator and regulator tubes. Crowbar ignitrons are installed across the oscillator and the regulator tubes, and a fast vacuum-switch circuit breaker is installed in the negative high-voltage power bus from the power supply. A major modification of the high-voltage power supply is the installation of new load-balancing circuits in each of the 20 Alpha-I cubicles which, in parallel, compose the power supply. The vacuum-tube circuits previously used obtained a signal from a resistor in the positive bus of each cubicle. With

Fig. 4.1. Simplified Circuit for High-Voltage Regulation in the 86-Inch Cyclotron.

the regulator in the system the positive bus is about 3.5 kv above ground, and the vacuum-tube circuits are no longer feasible. The new load-balancing circuits employ magnetic amplifiers which permit isolation of the high-voltage input signal from the remainder of the circuit.

OPERATION OF THE 63-INCH CYCLOTRON

The 63-Inch Cyclotron was available for experimental work approximately 77% of the scheduled operation time. The first dee-stem insulator failure in 26 months occurred as a result of an external water leak which in turn resulted in high-voltage arcing across the insulator. No other major outages were experienced. A breakdown of the down time is given below:

	Per Cent
Normal operational conditions	
Bakeout of machine	6.2
Beam improvement	3.3
Source changes and adjustments	2.8
Operational interruptions	
Electrical troubles	3.2
Vacuum troubles	3.8
Miscellaneous	3.8
Total	23.1

The machine was shut down for a total of about two weeks to permit necessary alterations of the magnet by the Isotopes Division and to permit repairs to associated water connections. This scheduled down time is not included in the operating schedule, which averaged about 53 hr/week for a total of approximately 44 weeks.

The type and number of N^{3+} bombardments made during this period are noted below:

Type of Bombardment	Number of Runs
Elastic and inelastic scattering	54
Light-particle spectra	25
Transfer reactions	160
Miscellaneous	9
Total	248

Some of the conditions and values of the 63-Inch Cyclotron during normal operation are:

Operating frequency	~4.855 Mc/sec
Magnetic field	15,000 gauss
Dee-dee potential	40-42 kv
Gas (nitrogen) flow rate (NTP)	1.4-1.5 cc/min
Beam energy	27.3 Mev $\pm$ 0.3
Vacuum	4×10^{-6} mm Hg
Arc conditions	
Filament current	360-520 amp
Arc voltage	150-250 v
Arc current	1.5-2.2 amp

OPERATION OF THE 86-INCH CYCLOTRON

The 86-Inch Cyclotron has operated in a relatively routine manner. The types and number of bombardments are outlined below:

Type of Bombardment	Number of Runs
Internal beam	
Service irradiations (isotope production)	91
Others (physics, development, etc.)	85
Deflected beam	
Service irradiations	42
Others (mostly physics)	204
Total	422

Of the scheduled operation time, which averaged 92 hr/week, the available beam time to the experimenter was about 68%. Operational down time was as follows:

	Per Cent
Normal operational conditions	
Baking out machine	8.8
Beam improvement	0.7
Source change and adjustment	2.0
Operational interruptions	
Electrical troubles	4.8
Vacuum troubles	5.4
Miscellaneous	10.3
Total	32.0

During a scheduled shutdown of about 300 hr the dees, septum, and channel coil were removed, reworked, and reinstalled.

Typical operating conditions for the 86-Inch Cyclotron are:

Operation frequency	13.241 Mc/sec
Magnetic field	9000 gauss
Dee-to-dee potential	400-500 kv
Energy	~ 23.0 Mev
Gas (hydrogen) flow rate (NTP)	2-3 cc/min
Plate voltage	17.2-18.7 kv
Plate current	12-14 amp
Vacuum	6×10^{-6} mm Hg
Arc conditions	
Filament current	350-450 amp
Arc voltage	165-250 v
Arc current	0.07-0.66 amp

The beam level is dictated by the type of target being bombarded and by the sponsor's experiment. Proton currents available vary from 0.1 to 20 μ a for external targets and from 30 μ a to a maximum of 2500 μ a on internal targets.

5. ACCELERATOR DEVELOPMENT

J. A. Martin

R. W. Boom

J. E. Mann

R. S. Livingston

Design of Cyclotron Analogue II is essentially complete, most of the components have been fabricated, and the machine is being assembled. The Analogue will be used to investigate problems anticipated in building an 850-Mev, fixed-frequency, AVF cyclotron, for which design studies are being made. Measurements of residual radiation in the 184-Inch Cyclotron at Berkeley were made as a basis for estimating the problem of servicing such a high-current machine. The Laboratory is cooperating with ORINS in the conceptual design of a bubble chamber for use with a high-energy accelerator.

CYCLOTRON ANALOGUE II

Cyclotron Analogue II, an eight-sector, spiral-pole, constant-frequency cyclotron is designed to accelerate electrons to at least 470 keV, where the intrinsic resonance $\nu_r = \frac{8}{4}$ is expected to defocus the beam radially. The magnetic field is designed to provide isochronous orbits well beyond this resonance so that if the conditions for resonance passage can be satisfied, acceleration to about 510 keV should be achieved. The magnetic field, in its main features, models the field for the proposed 850-Mev, high-current, fixed-frequency cyclotron. The Analogue will be used in a detailed experimental examination of conditions required for efficient beam extraction from such a machine.

During the past year the design and construction of Analogue II was nearly completed; the remaining large items are the average field trimming coils and the sector coils, both of which are about 50% complete. The design parameters of the machine are summarized below:

Cyclotron unit (c/ω)	16.000 in.
Central field (B_0)	41.926 gauss
Orbit frequency	117.399 Mc/sec
Axial focusing frequency, ν_z	0.2
Energy for $\nu_r = \frac{8}{4}$	~ 470 keV
Maximum energy	~ 510 keV

Magnetic Field Design

The air-cored coil system for Analogue II includes (1) the sector coils which produce the azimuthally varying field, (2) the main average field coils which supply most of the average field, and (3) a layer of 32 concentric trimming coils near the median plane. These trimming coils provide the fine adjustments of the field required for isochronous operation; with them the average field can be adjusted to within a few parts in 10,000 of the desired value. The arrangement of the coils and the support system is shown in Fig. 5.1.

Fig. 5.1. Exploded View of Cyclotron Analogue II Coils and Coil Support System.

For ease in fabrication, the original design¹ of the sector coils was converted to circular-arc geometry. Although some minor modifications of coil design were required to achieve a smoothly changing shape, these changes were accomplished without appreciably altering the focusing properties of the magnetic field.

The average field required for isochronous orbits was determined by extensive equilibrium orbit calculations (see Fig. 5.2). The difference between the isochronous average field and the average field of the sector coils is supplied by circular coils. Five "main coils" are used; they produce

¹Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047, p 48.

the required field to within a few per cent, except at the center of the machine. Spaced 2.5 in. off the median plane, these coils are located in slots in the main-coil-support casting. The sharp variations in magnetic field required at the center of the machine result from the field of the tips of the sector coils; they act as partial circular turns. It was found to be impractical to compensate these variations with coils located in slots in the mounting plate. Best results were obtained by locating two of the trimming coils, T_1 and T_4 , in line with the tips of the sector coils.

Final fitting of the magnetic field to high precision is accomplished by adjusting the currents in the 32 trimming coils mounted approximately 0.9 in. from the median plane. The fitting process includes readjustment of the currents in windings T_1 and T_4 . Figure 5.3 shows how the fields of the various coils combine to produce the required average field. Figure 5.4 gives the remanent error after adjustment of the windings of the 32 trimming coils. The "least-square" fitting method was applied throughout in calculations made with the Oracle. Table 5.1 summarizes the dimensions and the currents required for the several coils.

A problem requiring considerable attention was the design of the leads to connect, in series, the eight sector coils in each half of the coil assembly without (1) producing a large average field, which would require extreme precision in manufacture, or (2) producing a substantial contribution to the azimuthal variation (flutter), which would disturb the focusing properties of the already designed sector coils. The system evolved, shown schematically in Fig. 5.5, produces almost negligible flutter and contributes only 1% of the central average field. In essence, the system consists of two circular turns separated by $\frac{3}{8}$ in. and carrying current in opposite directions. The radial cross connections, because of their large distance from the median plane (8 in.), produce almost negligible flutter and zero average field. Errors as large as 0.02 in. with respect to the median plane can be tolerated, although the spacing between centers of the connecting bars must be accurately maintained.

Coaxial magnet-supply leads are used through the walls of the vacuum tank. Near the tank, special spacers accurately center the inner conductor. Beyond 3 ft from the tank edge, the spacer consists of polyethylene tubing. The upper and lower halves of the sector coil assembly are connected in series outside the vacuum tank. Because the cross section of this assembly is smaller than desired for free-air cooling, compressed air is directed through the tubes to cool both inner and outer conductors.

Fig. 5.2. Equilibrium Orbit Properties.

Fig. 5.3. Average Field Synthesis.

Fig. 5.4. Remanent Field Error After Trimming Coil Adjustment.

Table 5.1. Analogue II Average-Field Coil System

Coil	Radius (in.)	Turns ^a	Ampere-Turns	Central Field (gauss)	Current (ma)
M_1	3.200	815	-182.596	-13.814	-224.044
M_2	5.525	450	33.846	2.276	75.213
M_3	10.500	450	-40.647	-1.777	-90.326
M_4	13.120	396	386.958	13.831	977.166
M_5	17.582	896	1186.439	32.194	1324.151
T_1	0.800	194	73.592	14.312	377.394
T_2	1.227	194	10.749	2.373	55.123
T_3	1.653	194	-8.295	-1.729	-42.538
T_4	2.080	194	27.724	5.197	142.173
T_5	2.507	194	5.412	0.903	27.753
T_6	2.933	194	-3.644	-0.542	18.687
T_7	3.500	130	1.379	0.178	10.607
T_8	4.000	130	0.103	0.011	0.792
T_9	4.500	130	-0.113	-0.011	-0.869
T_{10}	5.000	130	-1.107	-0.104	-8.515
T_{11}	5.500	130	-0.502	-0.043	-3.861
T_{12}	6.000	130	0.315	0.025	2.423
T_{13}	6.500	130	1.054	0.078	8.108
T_{14}	7.000	130	0.487	0.033	7.346
T_{15}	7.500	130	-0.207	-0.013	-1.592
T_{16}	8.000	130	-0.410	-0.024	-3.154
T_{17}	8.500	130	0.487	0.027	3.746
T_{18}	9.000	130	-0.670	-0.036	-5.153
T_{19}	9.500	130	-0.018	-0.001	-0.138
T_{20}	10.000	130	-0.188	-0.009	-1.446
T_{21}	10.500	130	1.203	0.056	9.254
T_{22}	11.000	130	-2.037	-0.090	-15.669
T_{23}	11.500	130	1.328	0.056	10.215
T_{24}	12.000	130	1.084	0.044	8.368
T_{25}	12.500	130	-1.055	-0.041	-8.115
T_{26}	13.000	130	3.709	0.140	28.531
T_{27}	13.500	130	-13.886	-0.505	-106.815
T_{28}	14.000	130	24.693	0.867	189.946
T_{29}	14.500	130	-15.305	-0.519	-117.730
T_{30}	15.000	130	Not used		
T_{31}	15.500	130	Not used		
T_{32}	16.000	130	Not used		

^aWire size 28 was used for coils M_1 - M_3 , size 24 for M_4 , size 20 for M_5 , size 30 for coils T_1 - T_6 , and size 28 for coils T_7 - T_{32} .

Fig. 5.5. Lead System for Sector Coils.

Mechanical Design

The over-all precision of the coil system, apart from the accuracy of the components, is determined by the mounting arrangement. The sector coils, average field coils, and trimming coils must be precisely spaced in parallel planes to achieve the desired average field, as well as to prevent imperfect harmonics. To provide the required mounting precision, deep-ridged support-plate castings, 6 in. thick, of stable magnesium-aluminum alloy support the upper and lower coil assemblies, Figs. 5.6 and 5.7. The castings are spaced at three points with 3-in.-diam posts. The upper casting is supported directly upon the lower and is arranged to be substantially independent of minor misalignment of the vacuum tank and vacuum loading. The precision surfaces of the castings are flat to ± 0.0002 in. Each casting weighs about 600 lb and contains some 350 holes, most of which are located with a tolerance of ± 0.001 in.

Fabrication of the sector coils, Fig. 5.8, is about 50% complete. The technique used is essentially as described previously; some minor changes were made to assure flatness of the assemblies. The 16 pairs of channeled aluminum plates, Fig. 5.9, and the mating copper conductors are being produced with a numerically controlled milling machine to assure precision and exact duplication of design.

Fig. 5.6. Coil Support Plate: Upper Surface of Top Plate. The aluminum plate is 38 in. in diameter and 6 in. thick. All electrical and cooling leads are brought through the plate.

Fig. 5.7. Lower Coil Support Plate. The five coils for the main average field are recessed; the eight sector coils are attached to the plate; and the layer of 32 concentric coils are attached to the sector coils.

Fig. 5.8. Fabrication Technique for Sector Coils.

Fig. 5.9. Aluminum Plate for Support and Cooling of Sector Coil.

Design of the main average field coils followed conventional practice. The first of a pair fabricated was within ± 0.005 in. of specified dimensions. The second of a pair was machined to match the first within ± 0.001 in. During winding, careful attention was paid to details such as paper thickness, wire diameter, and number of turns per layer to assure symmetry. The actual dimensions of the coils will be used in the final magnetic field computations.

The circular trimming coils for Analogue II are being fabricated by the same method used for the Analogue I assemblies. The assembly consists of 32 concentric coils spaced 0.427 in. near the center and 0.500 in. at the outside. During winding, the assembly is supported on a winding plate which locates the winding rings and cover rings (see Fig. 5.10). The winding plate and the

Fig. 5.10. Detail of Trimming Coil Fabrication.

several plates from which were machined the winding rings and the cover rings are all matched-drilled for dowel, lead holes, and support screws; a numerically controlled (paper tape) jig borer (see Fig. 5.11) was used. Following the drilling operation, the plates are doweled and screwed together; the rings are then formed as shown in Fig. 5.12. After the coils are wound, the assembly is vacuum impregnated with an epoxy casting resin. When the resin is cured, the winding plate and cover rings, coated with a release agent during the winding process, are removed leaving a 33-in.-diam assembly of 32 coils, with a thickness of only $\frac{3}{16}$ in.

The vacuum tank, Fig. 5.13, is designed to eliminate some of the disadvantages of the Analogue I system. Large ports provide convenient access to the edge of the machine and will facilitate work with the beam extraction mechanism. The rear of the tank is designed to facilitate removal of the dee assembly for adjusting the electron injector and orbit-defining slits at the center of the machine. With this arrangement it will not be necessary to disturb the precisely aligned coil system except for major changes.

Fig. 5.11. Drilling Components for Trimming Coils with Numerically Controlled Jig Borer.

Fig. 5.12. Machining Winding Rings for Trimming Coils.

Fig. 5.13. Vacuum Tank for Cyclotron Analogue II.

A double vacuum system is used; atmospheric pressure loading is thus removed from the coil system and all organic insulating materials, such as epoxy resin, are excluded from the beam region. The high-vacuum system is pumped by a 6-in. mercury diffusion pump; the baffles are cooled with both Freon and liquid nitrogen. The two vacuum regions are separated by 0.020-in.-thick aluminum diaphragms. In case of vacuum accidents (withdrawn probes), the pressure in the two systems is automatically equalized to prevent damage to the diaphragms or coil structure.

Radio-Frequency System

The rf system of Analogue II operates at 117.3985 Mc/sec and consists essentially of the equipment shown in the block diagram in Fig. 5.14.

The rf regulator consists of a two-loop system; the first loop stabilizes the transmitter through screen voltage control of the final amplifier, and the second, which includes the dee, consists of two parallel paths for fast and slow error detection to provide a wide bandwidth. All components of the regulator are ready for installation. The rf output of the transmitter is constant to about 1 part in 3000 with the first loop closed; operation with the second loop closed has not yet been tested.

The "dee" for Analogue II is a quarter-wave strip line 33 in. in width and about 24 in. long. Tuning is accomplished by an adjustable shorting bar which contacts the dee and liner through

Fig. 5.14. Block Diagram of RF System for Cyclotron Analogue II.

spring-finger stock. Both the finger stock and the contact areas on the dee and the liner were gold plated in an effort to eliminate the erratic contact resistance encountered on Analogue I. The Q of the dee is about 600.

Power Supplies for Circular Coils

The precision required of the currents of the various circular coils is determined by the fraction of the central field that each produces and by the desired 1 part in 10^5 over-all field stability, see Table 5.1.

It was found that coils T_7 through T_{25} can be energized from a voltage-regulated power supply and controlled with series resistors having a low temperature coefficient. A 1000-ohm precision resistor in series with each coil allows the coil current to be read on a digital voltmeter directly in milliamperes. Each coil current is reversible and can be controlled from 0 to $\sim 200\%$ of the design current.

The stability required of the currents for coils T_1 through T_6 , T_{26} through T_{32} , and M_1 through M_5 is such that individual current-regulated power supplies are necessary. Since the stability of the supplies from Analogue I was found to be inadequate, new supplies were designed, Fig. 5.15. The open-loop gain (dc) of the USA-3 amplifiers is 10^7 . The over-all current stability of the power supply depends on the stability of the mercury reference cells and the feedback resistors. These items are mounted on a water-cooled heat sink in an effort to achieve the 1 part in 10^4 to 10^5 regulation required over a period of hours. Each of these power supplies will be metered by either a 1-ohm or 10-ohm precision resistor (depending on current) and a Leeds and Northrup K-3 potentiometer.

The supplies for coils T_7 through T_{25} are assembled. Supplies for T_{27} , T_{28} , and T_{29} are assembled and tested. The others are being built.

Fig. 5.15. Power Supplies for Analogue II Field Coils.

Power Supply for Sector Coils

The sector coils require 535 amp regulated to 1 part in 10^5 . A series transistor regulator, shown in Fig. 5.16, is being designed for this purpose. The Zener diode reference was found to have a total drift of, at most, 3 parts in 10^5 over a period of 24 hr, and a weekly total deviation not exceeding 5 parts in 10^5 . The series transistors, bus work, and shunt have been mounted. All the

Fig. 5.16. Power Supply for Analogue II Sector Coils.

parts have been acquired except for the driver amplifier and motor control, which have not yet been designed.

RESIDUAL RADIATION IN A HIGH-ENERGY, HIGH-INTENSITY MACHINE

R. W. Boom K. S. Toth A. Zucker

It is expected that one of the more serious problems connected with a high-intensity, 850-Mev accelerator will be due to the residual radioactivity induced in its components. This radioactivity may make maintenance difficult; in any event it should be considered in the over-all machine design. For this reason a study of residual radioactivity of the 184-Inch Cyclotron at Lawrence Radiation Laboratory, Berkeley, was made by a group from this Division. The opportunity was provided by a scheduled shutdown at Berkeley. The five-day study was conducted along three principal lines: (1) general survey of radiation levels in the cyclotron vault, (2) activation of foils placed near the cyclotron prior to shutdown, and (3) gamma-ray spectra from components in the magnet gap region.

The principal source of radiation background is due to activities in the dee structure, its support, and the liner. The meson and proton exit ports are the most intense external sources of radiation. Immediately after shutdown the radiation level at the surface of the cyclotron vacuum tank was 8 to 3 r/hr near the meson exit port, decaying with a half-life of ~ 3 hr. At other points on the surface the radiation level was of the order of 0.2 r/hr, half-life ~ 6 hr. After 48 hr the radiation level was about 7 mr/hr.

The radiation in the gap was due mostly to Cu^{64} (12.8 hr) and Co^{58} (72 days) produced in the copper dees and in the nickel constituent of a stainless steel structure. Neutron-induced activities were found to exceed proton-induced ones by two orders of magnitude. It was found from the foils left in the cyclotron vault for two days that the principal activities in iron were Mn^{52} and Mn^{56} , in copper Cu^{64} , and in aluminum Na^{24} .

The 850-Mev cyclotron would be expected to produce about 100 times the beam of the 184-Inch Cyclotron; for purposes of this study, the energy would be comparable to the Berkeley machine. Therefore it appears from this preliminary investigation that, after suitable cooling off, the 850-Mev cyclotron vault would have background radiation less than 1 r/hr. Movable shielding of moderate size will permit work on the machine. The cavities and other structures located in the gap will have to be handled remotely and repaired in a hot cell. Exit ports will have to be specially designed for remote handling. Sources of long-lived activity, such as nickel in stainless steel, should be held to a minimum, especially in the median plane.

The residual radiation hazard in the 850-Mev machine can probably be greatly reduced by controlled beam spilling and by careful engineering of components. A complete report of the study is being prepared.

HIGH-FIELD BUBBLE CHAMBER

In cooperation² with ORINS and several Southern universities the Electronuclear Research Division is participating in the preliminary conceptual design of experimental facilities to be used at a high-energy accelerator. Such a facility should (1) provide for an extremely good experimental program over a period of at least five years, (2) be sufficiently unique to present advantages over other instruments of its type, (3) be flexible enough to permit a wide variety of experiments, (4) be within the limits of present technology, and (5) be appropriate to the interests and backgrounds of the physicists most likely to use it. The following instruments were examined under the above criteria: bubble chambers, composite bubble chambers, luminescent and filament chambers, semiconductor matrices, and conventional counter systems.

After considerable study the group chose the high-field hydrogen bubble chamber as the most suitable instrument. Consideration of power requirements, cost, technical problems, and the physics for which such a chamber would most probably be used led the group to decide on a cylindrical chamber approximately 30 in. in diameter and 37 in. deep with a 100-kilogauss magnetic field. The axis of the magnetic field would be vertical; the chamber would be liquid expanded and illuminated from above and photographed from below. The field would be furnished by a cryogenically cooled solenoid.

Such a chamber would provide a high precision of measurement, since the fractional uncertainty in momentum measurement is

$$\frac{\Delta P}{P} = \frac{1.2}{\beta H \sqrt{L}} \quad (\text{for hydrogen}),$$

where β is the velocity of the particle, H the applied magnetic field, and L the track length. It follows that further improvement in momentum analysis for such chambers should be in the direction of providing stronger magnetic fields. The high magnetic resolving power brought to bear on short tracks, particularly those of the short-lived particles, is a unique feature of the high-field chamber. It is also possible to confine the paths of low-momentum particles to tight spirals, which makes it possible to observe their decay products or to determine accurately their energies from measured range.

The high field could be produced with an air-core magnet in three ways: (1) direct-current, water-cooled copper conductor, (2) pulsed-current, water-cooled conductor, and (3) direct-current, low-temperature conductors. A low-temperature solenoid was chosen because the combined cost of construction and operation is much less than (1) above and because (2) above is not feasible for a high-precision chamber since the problem of eddy-current heating in the chamber walls would require a long, uncertain development program with nonmetallic materials.

²R. W. Boom is a member of the ORINS-ORNL High-Energy Physics Study Committee, under the chairmanship of V. P. Kinney of the University of Kentucky.

Three choices for the low-temperature conductor are attractive: sodium at 10°K, aluminum at 20°K, and Nb₃Sn. The first two require equally large helium refrigerator systems (about 12,000-hp units) but are inexpensive to operate compared with copper at room temperature. Nb₃Sn is a superconductor at liquid-helium temperatures and, as such, offers the maximum reduction in the total power required. All three possibilities are being evaluated.

6. THE OAK RIDGE ISOCHRONOUS CYCLOTRON

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The building (Building 6000) for the Oak Ridge Isochronous Cyclotron (ORIC) was recently completed; beneficial occupancy was obtained on January 13, 1961, while the contractor (Foster and Creighton Company) continues with minor details. No changes in the over-all design or plan for the cyclotron or its components have been necessary. The design work for the cyclotron is well advanced, and orders have been placed for nearly all the major components, many of which have been fabricated and delivered. The components are being installed by H. K. Ferguson Company.

The ORIC is a variable energy, three-sector, azimuthally-varying-field, 76-in. cyclotron designed to accelerate various particles with e/m ratios from 1 to 0.125 up to energies of 145 Mev. The machine is designed to accommodate large ion currents up to 75 kw (1 ma of protons at 75 Mev). Although shown in previous reports,³ Table 6.1 and Fig. 6.1 are repeated here for convenience in describing the machine now under construction.

¹Instrumentation and Controls Division.

²Catalytic Construction Co.

³*Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047, p 54. Also R. S. Livingston and F. T. Howard, Nuclear Instr. & Methods 6, 1 (1959).*

Table 6.1. Design Specifications for ORIC

Performance goals	
Proton energy	Variable, up to 75 Mev
Heavy ion energies	Variable, up to 10 Mev/nucleon
Beam power, maximum	75 kw
Magnet, 3-sector, with slight spiral	
Pole diameter, base and tip	76 in.
Orbit radius, average maximum	31.5 in.
Magnet gap	
Hill	7.5 in.
Valley	28 in.
Central field, average maximum	17 kilogauss
Field rise with radius, maximum	8%
Winding, water-cooled aluminum	1.137 in. square
Power	
Valley coils	750 kw
Main coils	1000 kw
Weight	
Aluminum	9 tons
Steel	200 tons

Table 6.1 (continued)

Radio-frequency system, variable	
Oscillator frequency	7.5–22.5 Mc/sec
Orbit frequency, with harmonics	1.5–22.5 Mc/sec
3 and 5	
Dee	
Aperture	1.89 in.
Diameter	71 in.
Dee-to-ground potential	100 kv
Power	
Maximum input	500 kw
Output	350 kw

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Fig. 6.1. Resonance Conditions for Acceleration of Various Ions in ORIC.

MAGNET DESIGN AND FABRICATION

Approximately 100 runs were made during the past year on the quarter-scale model of the ORIC magnet; some 175,000 five-digit numbers were measured and recorded with the digital data-recording system.³ Information from these runs was used to determine the shape of the pole tips, the shape

and position of the valley coils, and the effectiveness of circular trimming coils in shaping the radial gradient of the average field. Design of the valley coils, the harmonic coils, and the trimming coils was completed, and the coils are now being fabricated. The full-scale magnet was tested to full power in its temporary location. The field measuring equipment was completed and tested, and is ready for installation as soon as the magnet is moved to the new building.

Pole-Tip Design

Six pole-tip geometries were examined on the quarter-scale model. Pole tip I had about the right average field shape for 75-Mev protons, but the flutter curve peaked at such a small radius that it was difficult to achieve focusing at large radii. By reshaping the pole tips several times and reducing the radial extent of the valley coils and moving them as far out as possible, the flutter curve was reshaped to rise linearly with radius and to peak at the deflection radius; the azimuthally averaged field, $\bar{B}$, was not adversely affected.

To provide the proper $\bar{B}$ for 100-Mev nitrogen with pole tip I required that the circular trimming coils produce a field correction at all radii up to the deflection point. The correction required with pole tip VI tapers off at the deflection point and is easier to achieve. The results obtained for pole tip I and pole tip VI are compared in Figs. 6.2, 6.3, and 6.4.

One of the more critical problems is achieving isochronism for particles of intermediate energy, such as 64-Mev nitrogen. For pole tip V this required that the circular trimming coils produce a

Fig. 6.2. Average Fields, Measured and Isochronous, for Pole Tips I and VI for 75-Mev Protons.

Fig. 6.3. Average Fields, Measured and Isochronous, for Pole Tips I and VI for 100-Mev Nitrogen Ions.

Fig. 6.4. Flutter for Pole Tips I and VI for 75-Mev Protons.

field of 2700 gauss at the center, Fig. 6.5. Pole tip VI reduced this requirement to about 1500 gauss, and at the same time increased the requirements for the circular coil correction for 75-Mev protons from 200 gauss to 1500 gauss. Pole tip VI represents a compromise between the requirements for 75-Mev protons and 64-Mev nitrogen ions.

Fig. 6.5. Average Fields, Measured and Isochronous, for Pole Tips V and VI for 64-Mev Nitrogen Ions.

Near the deflection region the shape of the flutter curve affects the rise of the magnetic field required to maintain isochronism of the high-energy protons. Proper shaping and positioning of the valley coils served to minimize the rise in field and gave better axial focusing; it also increased the driving term, which should be large for good deflection. Since the use of valley coils to increase flutter also decreased the average field, reducing the ampere-turns required in the valley for axial stability also helped to make the average field more symmetrical about the deflection radius.

Deflection Problem

There are several requirements for achieving efficient deflection. The symmetry of the field minimizes the third derivative of the average field with respect to radius. If the ratio of the driving term to the third derivative is large, then, after the amplitude of the beam oscillation exceeds the stable limits, the beam will gain sufficiently in radius in one turn to clear an electrostatic deflector. To escape the cyclotron in one-half turn, as required, the beam should be moving radially outward when it enters the septum. The present field configuration satisfies these requirements.

The design of a first-harmonic field which serves to increase the amplitude of oscillation of the beam and start resonance deflection is a critical feature. If the first harmonic reaches too far into the magnet, the beam quality will deteriorate rapidly. Use of multiple coils in a straightforward geometry confines the bump to the desired region and produces a large radial gradient as the beam enters the bump.

Field measurements were made on an electromagnetic coil assembly capable of producing a sharp local depression in the magnetic field. These measurements indicate that radial field gradients of 300 gauss/in. can readily be obtained and that gradients two or three times greater can be made if computations indicate that the larger gradients are necessary for high-quality beam deflection.

Circular Trimming Coils

It was at first assumed that the iron pole configuration which would require the minimum current in the circular coils would be the pole tips which produced a $\bar{B}$ approximately halfway between the isochronous fields for heavy ions and the field for protons. This approach must be modified because the valley coils substantially reduce the field at large radii. Nitrogen requires a $\bar{B}$ that is nearly constant with radius, but the isochronous field for protons must increase about 8% near the deflection radius. A more satisfactory balance between the requirements for light and heavy particles is obtained when the iron is shaped to favor the light particles at large radii, where the ΔR per turn is small and a small departure from isochronism produces a large phase slip between the accelerating voltage and the particles being accelerated. At small to intermediate radii it appears desirable to favor the heavy particle field requirements, or at least depart from the proton field requirements so that the $\Delta \bar{B}$ for nitrogen will not be excessive. The main function of the valley coils is to increase the flutter for the protons; they are not needed for nitrogen, which requires a much smaller flutter.

The problem of setting the various coil currents for a given ion and energy may turn out to be critical. There are indications that extensive measurements may be required to calculate the field produced by a given current in each coil. Although it involves an obviously nonlinear problem due to magnetic saturation, there are indications that a reasonable number of measurements will allow a linear approximation. The task is to determine settings close enough that, with adequate instrumentation such as phase shift at various radii and sampling probes, the operator can then tune to optimize the beam in a short time.

To evaluate the effect of circular coils, a set of seven pairs of coils was installed in the model. The fields from these coils were determined by measuring the total field, both with and without the individual coils energized. The field was also measured with several coils energized simultaneously to determine whether or not the sum of individually measured fields would closely approximate the resultant field of a group of coils. Preliminary results show that the calculated sums may not represent the field to a high degree of accuracy.

Full-Scale Magnet

Both mechanical and electrical measurements were made on the full-scale magnet, temporarily installed for the purpose. The magnet was excited at full power (1750 kw); water at building supply pressure was adequate for cooling. Measurements of the stray field around the magnet confirmed model measurements. A measurement of the gap between the pole base disks showed a taper which was corrected by machining. Condensed moisture accumulated inside the coil cases during storage was squeezed out from between the windings when the power was applied. Dry air was fed into the coils to prevent a repetition of this difficulty. Since the pole tips were substantially delayed in shipment, detailed magnet field measurements were not made in the temporary installation as planned.

The pole tips, valley coils, circular trimming coils, and harmonic coils are now being fabricated. The coils will be enclosed in vacuum-tight stainless steel cans to prevent off-gassing into the cyclotron. Asbestos, glass, and silicone varnish are used as insulating material to minimize radiation damage.

Magnetometer Positioner

A great number of preliminary magnetic field measurements will be required to determine the shape of the magnetic field and to determine the relative effect of the various coils used to optimize the field for a wide range of ions and ion energies. A large positioning mechanism, somewhat similar to the one used in the quarter-scale magnet, was fabricated and tested for use in the full-scale magnet. A Hall generator, used to measure the magnetic field, is mounted on the mechanism, which is capable of automatically positioning the magnetometer through a sequence of 7200 positions in the median plane. The radial and azimuthal accuracy of the positioning mechanism is ± 0.001 in. or less; the accuracy with respect to the median plane is ± 0.010 or less.

The main feature of the device is an aluminum 80-in. wheel which determines the azimuthal position at 2° intervals. The wheel is rotated by a pawl and air-driven pinion which engages the outer edges of the 180 slots in the periphery. The inner portion of the slots is thus protected and reserved for use as a reference surface for the locking cam.

The magnetometer carriage is mounted in a dovetailed machine slide placed along a radius of the wheel, Fig. 6.6. A cam on the carriage faces a slotted bar mounted on the wheel parallel to the dovetailed slide. The carriage is transported to an approximately correct position by a carriage-mounted reversible pawl which engages a sliding rack which is air-driven in strokes equal to the desired carriage travel. After the carriage is moved to the desired location, a splined shaft rotates the carriage-mounted cam into one of the positioning slots of the bar. The radial position of the magnetometer thus established depends only on the accuracy of spacing of the slots in the bar and the precision of the ways.

To obtain the desired azimuthal accuracy it was necessary to devise a means of cutting slots to within 6 sec of absolute position. The large size of the wheel made the problem more difficult. The method finally worked out made use of an Ultradex, an indexing head accurate to 0.25 sec. The work was done in the local (Y-12) shop, Fig. 6.7.

Fig. 6.6. Magnetometer Carriage on Positioning Wheel. Carriage moves radially in 1-in. steps.

Fig. 6.7. The 80-in. Precision Positioning Wheel for ORIC Magnetic Field Measurements. The wheel is slotted at 2° intervals with a maximum deviation of only 5 sec.

In operation the disk is mounted in an aluminum frame on closely fitted 9-in.-diam sleeve bearings. This frame is placed between the poles of the magnet and is centered axially by two specially designed air-operated tapered pins. All scanning operations are controlled by a system of sequential switches and relays interconnected with the automatic data recording system used with the quarter-scale model. Two methods of scanning are available: set radially every inch and scan azimuthally, or set azimuthally every 2° and scan radially. The radial scanning method will be used since the motion is faster.

The mechanism was tested, and is ready for installation as soon as the ORIC magnet is assembled. After the program of magnetic field measurements is completed the mechanism will be removed so that installation of the vacuum chamber and the rf system can be completed.

Magnet Power Supplies

A total of 21 separate power supplies are used in ORIC. A double-end, motor-generator set supplies 1000 kw for the main magnet coils and 750 kw for the valley coils. Power for the nine harmonic coils and the ten circular trimming coils is supplied with silicon rectifiers. The motor-generator set is now in place in the utilities room atop the shield structure (third floor), where the 19 rectifier power supplies are also being installed.

All magnet currents will be regulated to within 0.01%. The regulators for the two generators were tested on the quarter-scale magnet, and the two full-scale regulators are being fabricated. Regulators are being installed in each of the 19 power supplies for the AVF coils; space was provided in each module. Each regulator consists of a bank of series control transistors and three chassis of control equipment. The largest regulator uses 240 transistors. For ease of maintenance the transistors are mounted on water-cooled heat sinks in interchangeable units of five.

One of the three chassis in the regulators contains the reference supply, the low-level amplifier, and an appropriate feedback network for magnet compensation. A second chassis contains the general control and interlock functions and the voltage and power amplifier to drive the control transistors. The third chassis contains the amplifier and feedback circuit for the saturable-reactor control and the saturable-reactor current driver circuit.

The chassis for the regulators are being built so that any chassis will be interchangeable within the group of 19 supplies. Because each supply will have a different load (and there are four types of supplies) each unit will require a different feedback compensation network. For this reason the feedback compensation and other variable circuit elements are being put on plug-in boards which are associated with a particular supply and load. The chassis may be changed, but the plug-in boards will be kept in the supply.

A double-throw knife switch is mounted on each supply for reversing the polarity of the current supplied. The power supplies can be operated from either the cyclotron console and control board or at the supply site. For use in maintenance a portable control chassis, which can simulate the operation of the console for any one supply, is being built.

THE RADIO-FREQUENCY SYSTEM

The operating characteristics of the resonator were verified by test operation of the full-scale model; the coupling network between the resonator and the power amplifier was also tested. The rf amplifiers, oscillator, and their control systems are being developed and designed, Fig. 6.8. Design of the components of the resonator is complete except for the dee and liner. The dee stem, dee-stem house, support flange, and the handling equipment are ready to assemble. Tests have been made to determine the best technique for fabricating the unusually thin dee and liner.

Fig. 6.8. RF System for ORIC.

Resonator Measurements

The full-scale model of the rf resonator, with a single 180° dee as described previously,⁴ was installed in a test stand and its characteristics were measured. The resonant frequency range and the excitation power required for operation at 100 kv dee-to-ground verify the design calculations. The shorting plane can be moved to cover the full frequency range, Fig. 6.9. Fine tuning is obtained with a pair of trimming capacitors, Figs. 6.9 and 6.10. To avoid excessive power loss at reduced gap the motor drive was designed so that movement of the trimmer control is limited to a 1-in. range. Such a range of fine tuning requires the shorting plane to be positioned to within ± 0.1 in. at the highest resonant frequencies. The over-all drive system, including variable speed motor and synchro detector, for the shorting plane was designed to meet this tolerance.

The excitation power requirements and the Q for the ORIC resonator were extrapolated from measurements on the model, Table 6.2. The accuracy of the power measurement is certainly no

⁴Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047, p 54. Also R. S. Livingston and F. T. Howard, *Nuclear Instr. & Methods* 6, 1 (1959).

better than $\pm 10\%$; however it agrees well with the calculated value of about 175 kw at 22.5 Mc/sec. The values of Q lead directly to a minimum tolerance of ± 0.001 in. on the position of the trimmer capacitor. Such motion is equivalent to $\frac{1}{20}$ of the resonator bandwidth. The trimmers were designed to meet this requirement.

Fig. 6.9. Shorting-Plane Position vs Frequency, from Full-Scale Model of ORIC RF System. The circled extremes of the horizontal segments show the range of the trimming capacitors.

Fig. 6.10. Trimmer-Controlled Frequency Deviation, ORIC Full-Scale RF Model. The zero position corresponds to dee-to-trimmer spacing of 0.5 in.

Table 6.2. Power Requirements for Operation at 100 kv Dee-to-Ground, Extrapolated from Full-Scale Model Measurements

Shorting Plane Position (in.)	Trimmer Position (in.)	Frequency (Mc/sec)	Q	Power Required (kw)
128	1	7.29	7360	47.0
128	2	7.34	7500	47.3
74	2	9.57	6380	63.4
41	2	12.33	5880	79.6
20	2	15.90	4470	104
8	2	19.69	3440	140
2	1	22.40	2700	183
2	1.5	22.52	2760	178
2	2.0	22.58	2835	172

Resonator Drive

The most satisfactory way to couple the rf drive to the resonator appeared to be to insert a capacitor between the dee stem and a drive transmission line. This transmission line can operate with sufficiently low rf voltages that it can be brought out of the vacuum through an insulated bushing.

Given a physically small capacitor, C_c , between the dee stem and drive line, the input shunt resistance at a point θ electrical degrees from the coupling capacitor has a minimum value of

$$R_D = \frac{(X_{cc} - Z_0 \tan \theta)^2}{R} \cos^2 \theta.$$

In parallel with this resistance is a shunt capacitive reactance

$$X_D \approx Z_0 \cot \theta.$$

At this point

$$V_D = V_R \left(\frac{X_{cc} - Z_0 \tan \theta}{R} \right) \cos \theta,$$

where Z_0 = drive line characteristic impedance, R = resonator shunt resistance, and V_R = resonator voltages. For a lossless system ($R = \infty$), this point would be a voltage node. For the resonator to operate in this manner the frequency must be

$$\delta = \frac{2(f - f_0)}{f_0} = -\frac{R}{Q} \left(\frac{1}{X_{cc} - Z_0 \tan \theta} \right),$$

where f_0 = resonator natural frequency. Since R/Q does not depend on losses, resistive load changes do not affect the node position.

The network between the dee and the node operates as a 90° network. The addition of a second 90° network between the node and the driver tube leads to a relation between dee voltage and tube voltage which is a constant at each frequency, independent of resistive load. The 90° phase relationships can be used with a phase detector for tuning the system; the constant voltage ratio simplifies dee voltage regulation.

Since the coupling capacitor required proved to be physically large, 8 by 12 in., a more exact analysis based on coupled transmission lines were made. The results were in close agreement with the approximate results listed above.

The coupled line was installed on the full-scale rf model to check the computed values of voltage and phase. In Table 6.3 are listed the required power-amplifier plate voltages to reach the 100-kv peak voltage on the dee. The drive line between the power-amplifier plate and the voltage node was ~ 40 in. of 97-ohm line.

Table 6.3. Power-Amplifier Voltage Required for 100 kv (Peak) on Dee,
Extrapolated from ~ 200 v on Dee

Frequency (Mc/sec)	Power-Amplifier Voltage, Peak (kv)
7.16	4.3
9.5	7.2
11.7	9.8
14.7	13.6
18.0	15.0
20.42	15.0
21.35	14.5
22.5	12.9

In order that the drive line can have a fixed length and a fixed characteristic impedance regardless of frequency, the power-amplifier rf voltage must be lowered at the lower frequencies to maintain 100-kv dee voltage. Since the power required to excite the resonator and to supply beam losses drops from ~ 350 kw total at 22.5 Mc/sec down to ~ 50 kw at 7.5 Mc/sec, the tube can operate with the required lower plate voltage and slightly lower plate current, and remain efficient. The coupling network is shown in Fig. 6.11.

Fig. 6.11. Power-Amplifier Coupling Network, ORIC.

Power-Amplifier Driver Circuit

The power required to drive the RCA-6949 will be a maximum of about 2 kw at 2-kv rf peak. However, since the input capacity of the 6949 is between 1150 and 1550 picofarads, the circulating current in the grid circuit can be as high as 310 amp, rms, and the leads must be extremely short at 22.5 Mc/sec. A pi-network consisting of a variable, motor-driven, parallel stub line and vacuum capacitors to match a 4CX5000A air-cooled tetrode to the 6949 grid is being designed. A pi-network was chosen to provide neutralizing voltage for the 6949, as well as to permit operation of the 4CX5000A driver at 4 to 5 kv, rf peak.

Dee Voltage Regulation

A voltage regulator loop is being designed to maintain the dee voltage constant by controlling the control grid bias of the 4CX5000A, which will be operated as a linear amplifier.

Overload Protection

A spark in the resonator will be detected by loss of rf voltage and/or increase of power-amplifier plate current. The detector will then remove the excitation to the power amplifier by biasing off the 4CX5000A. After a short time, to be determined, the system will cut itself back on at a lower dee voltage, which will then rise back to the regulated value.

In the case of an arc-over in the power-amplifier tube, the overcurrent will be detected at the power-amplifier cathode and operate a crowbar on the dc plate voltage. In turn, the power-amplifier drive will be removed as above. Recycling is to be designed for the power-amplifier dc plate voltage and drive also.

Intermediate Amplifier

The intermediate amplifier consists of the 7558, 7212, and 7094 tubes in cascade between the oscillator and the 4CX5000A power-amplifier driver. The oscillator supplies about 3 v, rms, to the 7558, which operates as a class-A amplifier and, in turn, drives the 7212 as a linear amplifier. The 7094, operating in class C, supplies 300 v peak for the input to the 4CX5000A. A regulator loop is to be closed around the 7212 and 7094 to maintain the 300 v by controlling the 7212 bias. Circuitry for the amplifiers was designed, and a prototype of the regulator has been tested.

Oscillator

The stability of a self-excited oscillator was considered not quite adequate for ORIC. Crystal control was desirable, but continuous frequency adjustment was necessary. The oscillator being tested is based largely upon the Gertsch FM-6 frequency meter. As shown in Fig. 6.12, the 100- and 10-kc subharmonics are generated from a 1-Mc crystal. The signal from a master oscillator is mixed with a selected harmonic of 1 Mc and so on with harmonics of the 100 kc and 10 kc until a signal between 40 and 50 kc is obtained. This signal is compared in a phase discriminator with a stable free-running oscillator. The dc discriminator output then sets the bias on voltage variable

Fig. 6.12. ORIC Oscillator, Block Diagram.

capacitors in the master oscillator. An over-all accuracy and stability of one part in 10^6 is expected. A breadboard model of the oscillator is being tested.

Tuning

The oscillator will be mounted in the console, and the metering of all rf circuits will be on the control panel; however, all the rf amplifiers are to be mounted on the top of the dee-stem house in the cyclotron room. Therefore remote tuning controls are necessary. To tune the rf system, the operator must set the oscillator frequency, position the shorting plane, set the power-amplifier plate voltage, and set the power-amplifier plate and grid stubs to prescribed values. The resonator trimmers and amplifier tuning will be done by frequency servos. Table 6.4 lists the remote controls, both automatic and manual.

Tuning Servo

To measure relative phase difference at the various places listed above, the signals must be converted to a lower frequency for comparison. To do this an offset oscillator is ganged to the master oscillator and electronically controlled to always operate at 200 kc higher than the master oscillator. This oscillator signal is fed to frequency converters along with the signals from a phase probe at each detection point. Since phase information is retained in frequency conversion,

Table 6.4. Radio Frequency Remote Controls

Element Controlled	Phase Detector Between -	Phase (degrees)	Control
Upper dee trimmer	Dee voltage and node voltage	90	Auto-Manual
C_N	Node voltage and power-amplifier plate	90	Auto-Manual
C_{TP}	Power-amplifier plate and power-amplifier grid	180	Auto-Manual
C_{TD}	Driver plate and driver grid	180	Auto-Manual
$C_{T(IA)}$	7558 plate and 7558 grid	180	Auto-Manual
Lower dee trimmer			Manual
Resonator shorting plane			Manual
Power-amplifier plate stub			Manual
Power-amplifier grid stub			Manual
Power-amplifier plate voltage			Manual
Driver plate voltage			Manual

the phase difference of the 200-kc signals can be used to drive a phase detector. The phase detector then controls the servo amplifier. A breadboard version of the offset oscillator has been operated. The phase detection scheme was used, operating on open loop, on the resonator to control the dee trimmer capacitor and C_N , the node capacitor.

Dee Stem, House, and Support Flange

The dee-stem house and dee stem, Fig. 6.13, are cylindrical shells of copper-clad carbon steel to which have been added a flange at each end and stiffening rings along their length. The shells are $\frac{1}{2}$ in. and $\frac{3}{8}$ in. thick, respectively; the facing surfaces, which carry rf currents, are 20%-thickness copper clad. The steel surfaces are traced with copper water lines, BT Heliarc welded in place. For the dee stem, these lines were welded with a continuous unbroken fillet along each side of the line and joined at each end of the circuit. This was done to ensure complete sealing of any trapped volume beneath the lines.

The dee-stem support flange serves as a vacuum cover for the rf-ground end of the resonator system. It also serves as a support from which the dee stem is cantilevered. For access to the shorting plane mechanism the structure is provided with four removable cover plates, one of which is used to support a 20-in. oil diffusion pump. Designed into the structure are also numerous windows as well as small ports for entry of instrumentation and utility lines. The two tubes which position the shorting plane also pass through specially designed vacuum seals at top and bottom of the support flange.

These three structures, fabricated by the Nooter Corporation of St. Louis, have passed final inspection and are on hand awaiting final assembly. When assembled, they will form a quarter-wave coaxial stub whose effective electrical wavelength is varied by means of a movable shorting plane.

Fig. 6.13. Section of ORIC Showing Main Features of Resonant Structure and Vacuum System.

Shorting Plane

As previously described,⁵ the rf shorting plane is composed of 48 identical units; each contains two pivoted contact arms actuated by a bellows. By revolving the arms (shoes) about two fixed centers a connecting foil can be used with a minimum of distortion during operation. Each shoe is divided into several fingers by radial saw cuts to allow conformity to surface irregularities of dee stem and dee-stem house wall. Any one of the 48 units may be replaced by withdrawing the shorting plane into the dee-stem support flange to within reach of one of the access ports; six spares are being fabricated.

The shorting plane is positioned with two stainless steel tubes which extend out through vacuum seals in the support flange. They are operated by an external system of chain-driven screws. The mechanism permits the shorting plane to be moved about 12 ft along the dee stem.

Trimming Capacitors

Along the accessible periphery of the dee, both above and below the stem attachment, are the trimming capacitors. Each capacitor is a flat water-cooled copper plate, conforming to the dee curvature, hinged at one end, and positioned by the action of a cam and follower. There is an un-cooled copper foil over the mechanical hinge joint to carry the rf current.

The mechanism which varies the capacitor gap is a linear-translation, screw-driven piston which is linked to the cam-driven arm. A two-phase servomotor drives the screw which drives the piston, rotating the cam to the desired position. Because of the great reduction within the system, discrete movements of less than 0.001 in. should be obtained.

Dee, Mechanical Design

The ORIC dee is 70 in. in diameter but has an over-all thickness of only 2.75 in.; the aperture is $1\frac{7}{8}$ in. It is an unusually large dee for a wall thickness, including the carbon lining, of less than $\frac{7}{16}$ in. To conserve aperture, many schemes for fabrication of a thin dee wall were examined. Two good possibilities are considered. No choice of technique has yet been made, but there is a possibility that one will be used for the dee and the other for the liner.

One method involves the attachment of flattened (tubing) coolant passages to hard drawn copper sheet stock by Heliarc brazing with pure BT silver solder. Many samples have been made by this technique. When used with a Heliarc gun this solder (72% copper-28% silver) requires no flux and exhibits a great deal more flow than copper. It does not decrease the over-all hardness as much as torch or furnace brazing. This is an important point because annealed copper in such large sheets is very difficult to hold flat.

Another method which has been thoroughly examined is copper sheet stock into one side of which the desired coolant channels have been cut and to which a solid sheet of copper is then

⁵Electronuclear Research Div. Ann. Progr. Rept. Mar. 1, 1960, ORNL-3047, p 54. Also R. S. Livingston and F. T. Howard, *Nuclear Instr. & Methods* 6, 1 (1959).

bonded by furnace brazing, with a foil of Litho-Braze, while maintained under high-vacuum conditions. In this method the copper sandwich containing the braze-metal foil is placed in a suitable thin-walled steel envelope, evacuated, and then furnace brazed.

Experience with this process, although not conclusive, has been encouraging. In tests there has been some puddling of the braze metal in the channels; on one occasion the braze metal alloyed through the copper plates, due to excessive temperature and time. A thinner foil and better control of the process should eliminate these objections. The bonds formed are exceedingly strong; some of them have withstood 4000 psi over channels $\frac{1}{2}$ in. wide.

VACUUM SYSTEM

In addition to the dee-stem house mentioned above, the vacuum system includes the accelerating tank, vacuum manifold, baffles, and pumps. These items have been fabricated and are now being tested.

Accelerating Tank

The tank is 10 ft by 10 ft and 34 in. thick, roughly square. In both of the larger walls there are circular holes to accept the pole base disks. Most of the periphery of the tank is occupied by cover plates and ports. Because of its position with respect to the magnetic field, all material of the tank is nonmagnetic series-300 stainless steel. All welds are of the full-penetration type and were carefully controlled and dye checked during fabrication. The walls of the tank are of 0.75-in. material to allow flexing with changes of the magnet gap.

Vacuum Manifold, Baffles, and Pumps

The diffusion manifold attaches to the lower portion of the accelerating tank on the side opposite the dee stem. This unit serves as a manifold and as a mounting for two 32-in. oil diffusion pumps and their Freon baffles, and also contains two air-operated 32-in. gate valves. The Freon baffles have only one flange and are designed for almost complete insertion into the manifold. This allows the vacuum side of the frame to be used as a valve seat and also allows more headroom. The two 32-in. pumps are standard items of the new short, high-speed type.

ION SOURCE AND PROBE

Controls are available at the cyclotron console for optimizing the position of the ion source during operation and for scanning the beam with a probe. Since high radiation levels may be encountered in the cyclotron vault, even after shutdown, the source and probe mechanisms are also mounted so that they can be installed and removed with remote controls.

A compound carriage for the source and probe is being assembled and tested. The source can be moved in and out, moved to 4 in. above or below the center, and rotated $\pm 5^\circ$. The probe can be

moved 40 in. for radially scanning the beam and rotated 90° for transverse scanning. The motorized carriage makes all functions operative within the length of the tag lines; with the addition of an automatic tag-line disconnect the source and probe can be transferred to any point in the shop area.

A standard Oak Ridge-type ion source is used, similar to the sources developed for the 86-in. and 63-in. cyclotrons. The machined graphite parts are modified somewhat to simplify assembly and replacement. The filament is of 0.170-in. tantalum and operates at 2 to 3 v and 500 amp.

CONTROL SYSTEM

Cyclotron control and measuring equipment is located in rooms adjacent to the shielded areas. The control room on the first floor contains all controls and instrumentation which pertain to normal operation of the machine. The relay cabinets are immediately above the control room near the conduits entering the experimental areas. The main power supplies are all in the utilities room on top of the shielded area. All control connections to the cyclotron will pass from the console or control panel to the relay cabinets and from there to the equipment. A counting room adjacent to the control room will serve as the data acquisition area for experiments. A system of patch panels located in the experimental areas, the control room, and the counting room will provide a convenient method of interconnecting experimental equipment without the necessity of installing wires and cables for each experiment.

Cyclotron Controls

The cyclotron control panel, console, and two relay cabinets are scheduled for delivery about March 1. The console is about 50 in. wide and 32 in. deep with two 40-in. wings mounted at an angle; a desk top is installed in the U-shaped area for convenience to the operator. Instruments and controls were assigned space on the console according to their importance to operation of the machine. The beam current indicator is immediately in front of the operator, while those controls which are expected to be frequently adjusted are immediately on either side of the beam meter.

The control panel consists of ten sections of ORNL standard 24 × 24 in. control panels assembled in 4-ft modules. A graphic layout of the external beam system is displayed on the control panel immediately in front of the operator. Vacuum valves are operated by push buttons on the graphic panel. Cooling water circuits for the beam optics components are monitored for flow failure and indicated on the graphic display. The source gas selection system will be displayed and controlled from a smaller graphic display to the right of the vacuum graphic. Annunciators which call attention to parts of the system which are operating improperly are located across the top of the control panel. Instrumentation of interest to the cyclotron operator but of secondary importance to operation occupies the rest of the control panel space.

Instrumentation

The main magnet coils and the valley magnet coils will be protected against overtemperature by a bridge system set to sound an alarm on a predetermined value of voltage unbalance. An excessive temperature rise in any one of the coils will unbalance the bridge and activate an alarm. Power

will be removed from the main magnet coils if cooling water failure occurs to any one of 16 coolant circuits. The valley coils will have a flow interlock connected to the cooling water return header from each valley group. Harmonic and trimming coils will be protected against water failure by flow interlocks on each coolant circuit.

Gas flow rates to the ion source are expected to be of the order of 4–10 cc/min STP. A special differential pressure flow transmitter was designed; the instrument consists of a standard type 13A differential pressure flowmeter with an integral sapphire jewel orifice with a 0.003-in. aperture. The orifice was sized so that a hydrogen flow of 10 cc/min STP will produce a differential pressure of 20 in. H₂O. Preliminary tests indicate that the flowmeter will respond to a change in source gas flow much more rapidly than existing equipment. The flowmeter in conjunction with a controller and valve will be capable of maintaining source gas flow at a predetermined value set by the operator at the console. The present method of source gas control is with a manually set valve.

The beam current indicator and integrator, an Elcor model A-309A unit, provides current indication, current integration, and automatic shutdown of the cyclotron at a predetermined integrated charge. Current range is 3 nanoamperes to 1 ma. The beam current is indicated on the meter at the console and recorded on a strip chart at the control panel.

Indications of the positions of the source, probe, and rf tuning elements will be provided by means of synchro transmitter and receiver units. Measurements of effects of magnetic fields on accuracy indicate that errors will be less than 2° in a 250-gauss field. The error appears to be a result of substantial third harmonic components in the output of the synchro transmitter. The effects of the harmonic component may be reduced by orienting the axis of the device perpendicular to the lines of magnetic flux.

The flow of demineralized water in the low-pressure system, which cools the dees and other sensitive parts of the system, is controlled with a three-way valve that bypasses a portion of the warm water returned from equipment around the heat exchanger. Flow is controlled so that the temperature of the cooled water returned to the cyclotron is held constant at about 100°F.

Radiation Protection

Personnel protection against radiation will be provided by a series of interlocks and instruments located throughout the area. A target selector switch determines which interlocks will be operative and which experimental areas can be entered without affecting cyclotron operation. Keyed interlocks and permissive circuits will be included to assure that the operator knows which shielded areas have been entered.

ORIC BUILDING

The Laboratory obtained occupancy of the cyclotron building on January 13, 1961; the contractor had been given a total of 28 days extension beyond contracted completion date due to bad weather,

work stoppages, and delays in deliveries. Deviations from the contract design increased the lump-sum contract \$68,000, to a \$1,484,700 total.

After some delay in delivery, the shielding doors were installed during the summer. The doors are crane-hinged and filled with barites concrete; their specifications are as follows:

Door No.	Opening (ft)	Thickness (ft)	Weight (tons)	Closing Force (lb)
L-102	4 × 7	5.5	30	40
L-103	4 × 7	5.5	30	40
L-104	11 × 15, two parts	5.0	35 each	40
L-105	5 × 7	5.5	30	40

Adjustments are still being made to make the pair of large doors meet the closing force specified for manual operation.

The two zinc bromide windows installed in the shielding passed hydrostatic tests. Phenoline paint applied to the window shells had blistered; both windows were cleaned and repainted by the vendor.

The large external access ports to the cyclotron vault and the larger experiment room were closed with a total of 54 concrete blocks, 10 tons each. The blocks were poured in place; as each block hardened a wax coating was applied before the next block was poured. They have since been removed and replaced with no difficulty.

Checkout of the vacuum system installed by the contractor is under way; a few leaks have been found in the welding. The system installed consists of five 2-hp and three 15-hp mechanical pumps and the associated headers and remote lines to the three shielded areas. The motor-generator set, air compressor, dry-air system, cooling water system, and other equipment are now being checked. To date no serious problems have been encountered.

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PAPERS PRESENTED AT SCIENTIFIC AND TECHNICAL MEETINGS

Southeastern Section of American Physical Society, Gatlinburg, Tennessee, April 7-9, 1960

J. B. Ball and C. D. Goodman, "Nuclear Structure Information from Proton-Induced Reactions at 22 Mev."

R. S. Bender and R. H. Bassel, "Magnetic Field Design and Orbit Calculations."

C. D. Goodman and J. B. Ball, "Apparatus for Simultaneously Measuring (p,p') , (p,d) , (p,t) , and (p,α) Spectra and for Processing the Data."

E. D. Hudson and R. S. Lord, "Magnetic Measurements for ORIC."

R. S. Livingston and R. J. Jones, "Oak Ridge Isochronous Cyclotron."

R. E. Worsham, S. W. Mosko, and N. F. Ziegler, "The Radio-Frequency System for ORIC."

A. Zucker, "Rainbow Scattering of Heavy Ions."

American Physical Society, Washington, D.C., April 25-28, 1960

J. B. Ball, " (p,t) Differential Cross Sections at 22 Mev."

E. G. Funk, C. F. Schwerdtfeger, J. W. Mihelich, and B. Harmatz, "Decay of Eu^{146} ."

J. W. Mihelich, B. Harmatz, and T. H. Handley, "Nuclear Levels of Odd-A Nuclei for Odd Neutron Numbers 99 to 107."

J. J. Pinajian, J. L. Need, and W. H. Webb, "Excitation Function for $\text{Ni}^{58}(p,pn)\text{Ni}^{57}$, $\text{Ni}^{58}(p,\alpha)\text{Co}^{55}$, and $\text{Ni}^{64}(p,n)\text{Cu}^{64}$."

C. F. Schwerdtfeger, J. W. Mihelich, and B. Harmatz, "Decay of Eu^{147} to Levels in Sm^{147} ."

K. S. Toth and O. B. Nielson, "Decay Studies of Dy^{155} and Dy^{157} ."

T. F. Tuan, R. H. Bassel, and R. M. Drisko, "The Effect of Multiple Scattering and Pick-up Reactions."

Second Conference on Reactions Between Complex Nuclei, Gatlinburg, Tennessee, May 2-4, 1960

M. L. Halbert and A. Zucker, "Inelastic Scattering of N^{14} by C^{12} ."

C. E. Hunting, "Light Particles from Nitrogen-Induced Reactions."

K. S. Toth, "Angular Distribution of N^{13} from N^{14} on N^{14} ."

A. Zucker and M. L. Halbert, "The Elastic Scattering of Nitrogen from Light Elements."

Second All-Union Conference on Nuclear Reactions at Low and Medium Energies, Moscow, USSR, July 21-28, 1960

A. Zucker, "Heavy Ion Research in the United States."

A. Zucker, "Nuclear Reactions and Scattering with 28-Mev Nitrogen Ions."

International Conference on Nuclear Structure, Kingston, Ontario, August 28-September 3, 1960

R. H. Bassel and R. M. Drisko, "Optical Model Analyses of Heavy Ion Scattering."

C. D. Goodman and J. B. Ball, "Single Particle Levels in Iron Isotopes Studied with (p,d) and (p,t) Reactions."

M. L. Halbert and A. Zucker, "Inelastic Scattering of N^{14} by C^{12} at 27.3 Mev."

A. Zucker (Invited Paper), "The Study of Nuclear Structure with Heavy Ions."

American Physical Society, Berkeley, California, December 29-31, 1960

K. S. Toth, "Neutron Transfer to Excited States in N^{15} in the $\text{N}^{14}(\text{N}^{14},\text{N}^{13})\text{N}^{15}$ Reaction."

MISCELLANEOUS ACTIVITIES OF THE ELECTRONUCLEAR RESEARCH DIVISION

The Division continues to engage in a variety of activities as part of its research function and as a responsibility to the scientific community as a whole. The following items deal with scientific meetings, university relations, seminars, and related matters.

SECOND CONFERENCE ON REACTIONS BETWEEN COMPLEX NUCLEI

Members of the Electronuclear Research Division organized this second conference on heavy-ion reactions. A total of 112 physicists and nuclear chemists from 30 institutions in the United States and abroad participated; 40 papers were presented. The conference was a lively one, with a great deal of informal discussion. The proceedings of the conference were edited by members of the Division, were published by John Wiley and Sons, and appeared five months after the meeting.

UNIVERSITY RELATIONS

The Division now has two graduate students doing Ph.D. thesis research in nuclear physics or chemistry. One, from the University of Tennessee, is working with the heavy-particle physics group. The other, from Michigan State University, is engaged in radiation chemistry research with 22-Mev protons.

Arrangements are made with two universities for one student-trainee from each on the cooperative work-study plan.

During the past summer four graduate or undergraduate students were temporarily assigned to various groups.

Two research participants, faculty members of Southern universities, were in residence during the summer of 1960.

Members of this Division presented many lectures at various universities, both in the South and in other parts of the country, including lectures under the ORINS-sponsored Traveling Lecture Program.

One trip was made to the University of Arkansas under the Visiting Scientist Program sponsored by the American Institute of Physics.

SEMINARS

Nineteen seminars sponsored by the Division were given either by Laboratory personnel or by invited speakers from other institutions.

INTERNAL DISTRIBUTION

1. C. E. Center	65. C. H. Burbage
2. Biology Library	66. J. H. Cupp
3. Health Physics Library	67. F. A. DiCarlo
4-6. Central Research Library	68. H. L. Dickerson
7. Reactor Division Library	69. Pat A. Dunigan
8-27. Laboratory Records Department	70. C. B. Fulmer
28. Laboratory Records, ORNL R.C.	71. C. A. Gault
29. ORNL - Y-12 Technical Library,
Document Reference Section	72. C. D. Goodman
30. A. M. Weinberg	73. M. L. Halbert
31. J. P. Murray (K-25)	74. J. L. Hamilton
32. R. G. Jordan (Y-12)	75. B. Harmatz
33. J. A. Swartout	76. F. T. Howard
34. E. H. Taylor	77. E. D. Hudson
35. E. D. Shipley	78. C. E. Hunting
36. S. C. Lind	79. R. J. Jones
37. M. L. Nelson	80. R. S. Lord
38. W. H. Jordan	81. F. E. McDaniel
39. C. P. Keim	82. J. E. Mann
40. F. L. Culler	83. M. B. Marshall
41. A. H. Snell	84. J. A. Martin
42. A. Hollaender	85. S. W. Mosko
43. M. T. Kelley	86. E. Newman
44. G. E. Boyd	87. E. L. Olson
45. K. Z. Morgan	88. G. A. Palmer
46. T. A. Lincoln	89. J. J. Pinajian
47. A. S. Householder	90. A. E. Pugh
48. C. S. Harrill	91. E. G. Richardson
49. C. E. Winters	92. A. W. Riikola
50. H. E. Seagren	93. L. B. Schneider
51. D. Phillips	94. D. M. Smith
52-53. P. M. Reyling	95. W. R. Smith
54. G. C. Williams	96. K. S. Toth
55. R. W. Johnson	97. C. L. Viar
56. J. A. Lane	98. R. E. Worsham
57. R. A. Charpie	99. N. F. Ziegler
58. R. S. Cockreham	100. A. Zucker
59. R. S. Livingston	101. W. A. Fowler (consultant)
60. J. B. Ball	102. H. Feshback (consultant)
61. R. M. Bassel	103. M. Goldhaber (consultant)
62. R. S. Bender	104. M. S. Livingston (consultant)
63. R. W. Boom	105. J. R. Richardson (consultant)
64. G. L. Broyles	106. J. H. Van Vleck (consultant)
	107. J. A. Wheeler (consultant)

EXTERNAL DISTRIBUTION

108. Division of Research and Development, AEC, ORO
109-736. Given distribution as shown in TID-4500 (16th ed.) under
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Progress reports have been issued by the Electronuclear Research Division for the periods ending on the dates listed below:

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ORNL-1270	December 31, 1951, Part II
ORNL-1315	March 31, 1952, Part II
ORNL-1339	March 31, 1952, Part I
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