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Abstract. This paper presents a general description of a small cyclotron built and used by undergraduates of the Iowa State University Physics Department. This machine was the first operating small cyclotron capable of useful nuclear reactions to be built by an undergraduate group. Specifications of the machine are given. The paper also includes a short review of cyclotron action and a description of some of the auxiliary equipment used in the ISU cyclotron laboratory.

The Iowa State University undergraduate cyclotron project was begun in the fall of 1954 when several undergraduate physics students (1) decided to build their own cyclotron as a joint project of the Undergraduate Physics Club and of the Physics Department laboratory program. Aided by Dr. D. E. Hudson of the Physics Department, the students made plans for the machine. Several industrial firms generously contributed materials to the project (2). The project was a long and laborious one, but the efforts were well-rewarded when the first beam was obtained three years later, in the spring of 1957. Since then, the cyclotron has proved to be an excellent laboratory instructional device. It has been used in conjunction with the undergraduate laboratory program and with the National Science Foundation Undergraduate Research Participation program. The cyclotron has also provided material for two Masters' theses.

The ISU cyclotron (Figure 1) is a machine capable of accelerating protons to an energy of 1.5 million electron volts. If one were to classify this machine, the first adjective to come to mind would be "small"; and, indeed, it is small compared to the behemoth accelerating machines of today. The ISU machine is, however, commensurate with the first useful cyclotrons built in the early thirties.

Small cyclotrons have been built by groups of students insecondary schools (3) and colleges (e.g., Oberlin College). However, the ISU machine was the first operating "small" machine known to the author which was large enough for serious work in nuclear physics and which at the same time was built and manned essentially by undergraduates for exclusive use in an undergraduate teaching program (4).

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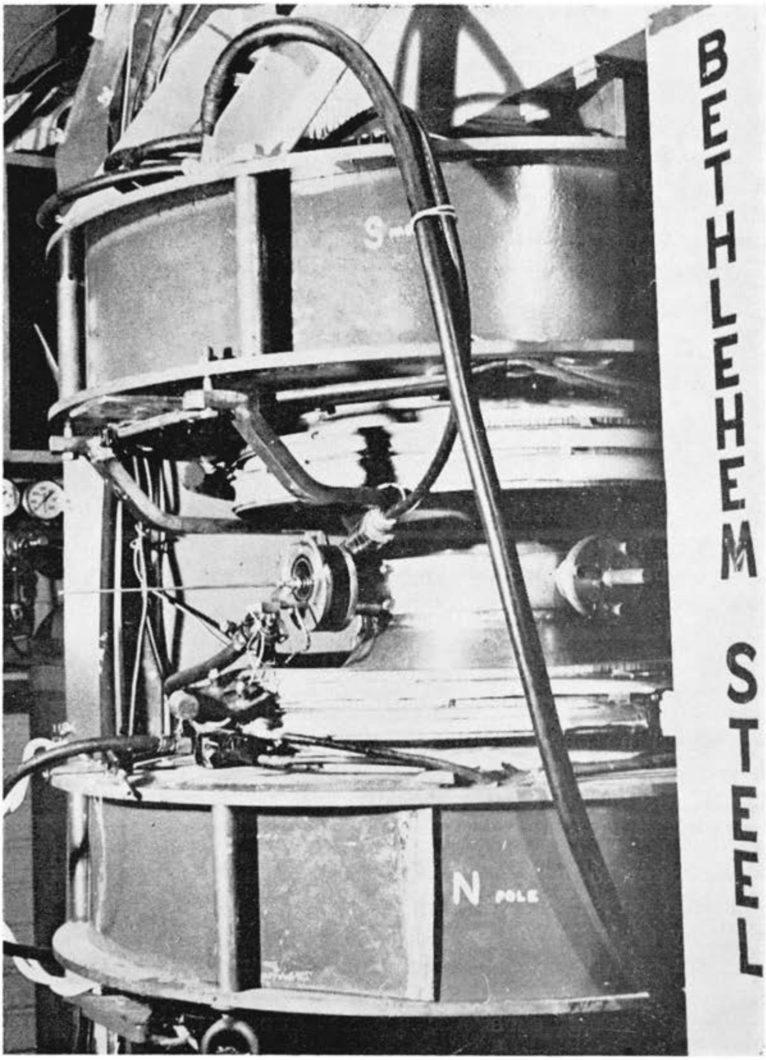

Figure 1. The Iowa State University cyclotron. The large cylinder-shaped objects marked "S" and "N" are the magnet coils. The magnet core, marked "Bethlehem Steel", is partially visible. The dee box is seen in the center of the yhoto between the tapered pole pieces of the magnet core. The distance from the top of the upper coil to the bottom of the lower coil is 25 inches.

Extensive descriptions of small cyclotrons appear in the literature. (5, 6). A rather complete description of the present machine has been given by Crosland (7). Descriptions of undergraduate theoretical work with the ISU machine by Mueller (8) and of the ISU experimental program by Burns (9) appear in this journal.

Cyclotron Operation

The cyclotron, developed by Lawrence and Livingston in 1930, was the first machine capable of accelerating atomic particles to energies high enough for extensive investigations of the atomic nucleus (10). In the cyclotron, a charged particle is constrained to move in a circular orbit by a strong magnetic field. In the non-relativistic case, the particle will circulate in the magnetic field with a frequency independent of the orbital radius and the energy of the particle. This frequency of revolution is given by the cyclotron resonance formula

$$f = Be/2\pi m,$$

where B is the magnetic field strength, m is the mass of the particle, and e is its charge; all units are MKS.

As shown in Figure 2, an electric field is introduced tangent to the particle orbit by placing a potential across a gap between two electrodes called dees. Every time the charged particle crosses the gap, it will receive an increment of energy from the electric field. The magnetic field in Figure 2 is perpendicular to the electric field. Magnetic flux lines come out of the plane of the paper.

The gap between the dees extends across a diameter of the orbit; and the ion will, consequently, cross the gap twice in each revolution. Since the direction of the second crossing is opposite that of the first, the electric field must be reversed with each consecutive crossing if the ion is to be accelerated each time.

According to the cyclotron resonance equation, the frequency of revolution is constant; so the accelerating voltage may be supplied by a constant frequency a-c source. If the magnetic field strength and the frequency of the a-c source are adjusted to satisfy the resonance equation, the particle will receive an increment of energy each time it passes through the electric field. The radius of the orbit increases with the energy; and if a particle is started at the center of the magnetic field, it will spiral outward as it gains energy. When the particle attains a high energy, and, hence, a large radius, it impinges upon a material sample called a target. The high energy particle interacts with a nucleus in the target and a nuclear reaction takes place.

Constructional Details

For purposes of description the machine may be broken down into three major component complexes: the magnet, the radio frequency power source, and the dee box or vacuum chamber.

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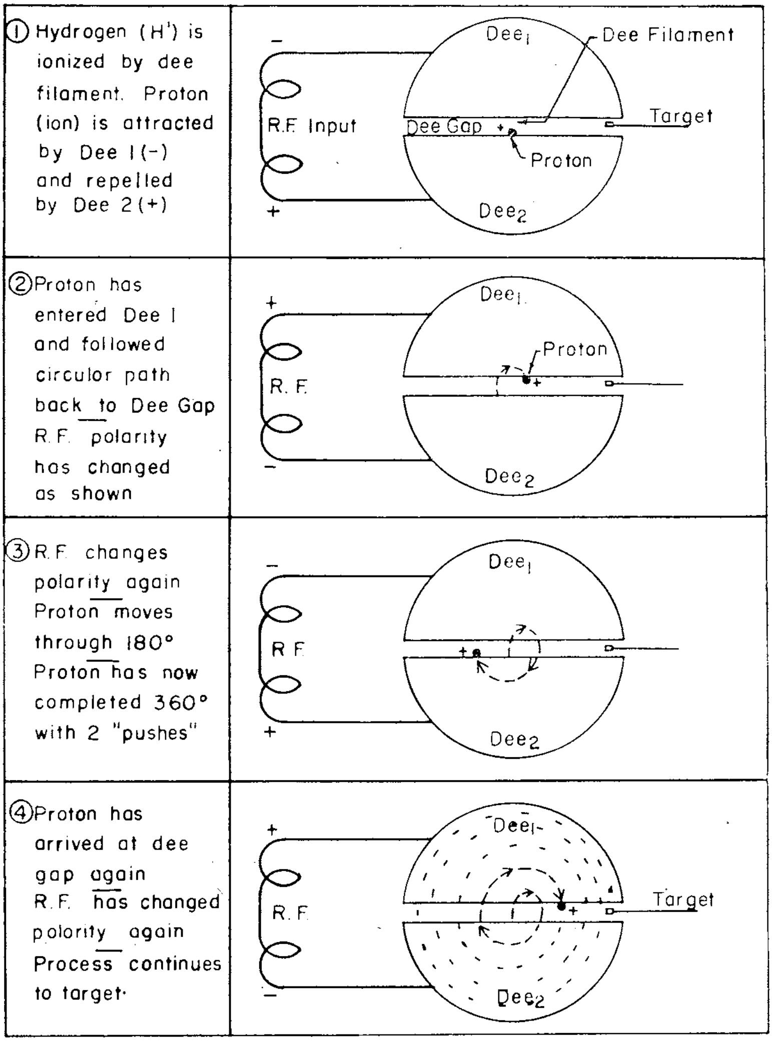

Figure 2. A schematic view of the dees showing the path of the accelerated proton. The magnetic field is perpendicular to the plane of the dees (from Crosland).

The Magnet

The cyclotron magnet is a large electro-magnet capable of producing a very uniform 17,000 gauss field. The magnet consists of coils of hollow copper tubing wound on a two-ton core of mild steel. Figure 1 shows the magnet. The magnet coils are 33 inches in diameter. The magnet has tapered poles, the poles being tapered from 12-inch pole stems to 10-inch pole faces. There is a 0.7 inch thick shoulder at the pole face. This configuration is pictured in Figure 5. The tapered pole shape and peripherally

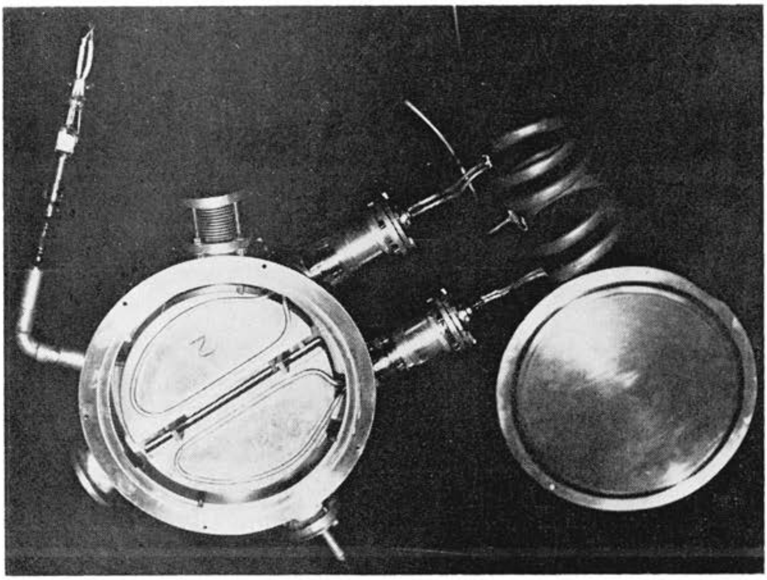

Figure 3. The dee box. The dees are the "D" shaped objects. The copper tubes that carry cooling water are seen near the edge of each dee. The copper helix on the right is the coil of the radio frequency tank circuit. The lid of the dee box is seen at the lower right. The bakelite spacers between the dees are for jigging purposes only and are removed when the machine is in operation.

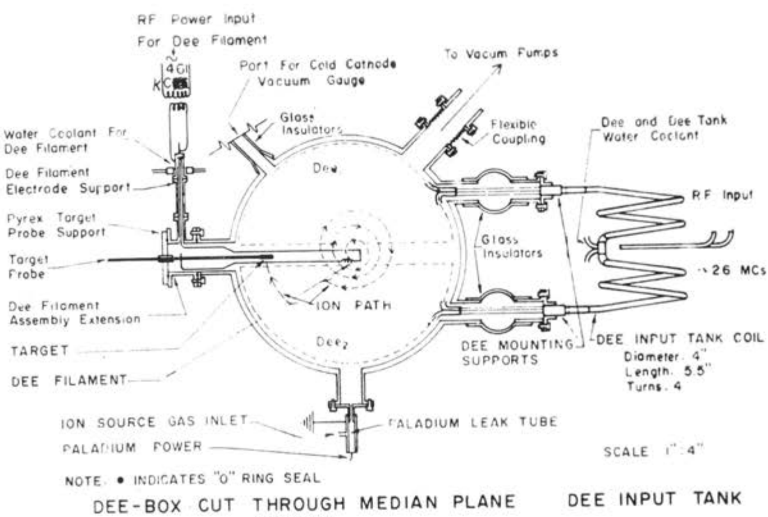

Figure 4. A schematic view of the dee box (from Crosland).

placed steel shims contribute to the uniformity of the field. Direct current is supplied to the magnet coils by two motor-generator sets. These deliver to the magnet 20 kilowatts of electric power, which is dissipated by water circulating through the coils.

The Radio Frequency Power Source

The radio frequency power source is used to supply the accelerating potential to the cyclotron dees. The final amplifier of the r.f. source consists of two type 833 vacuum tubes in push-pull. Their output power is two kilowatts at a frequency of 25.68 megacycles per second. The frequency of operation is controlled by quadrupling the 6.417 megacycle output of a war surplus Command transmitter. The output of the r.f. unit is inductively coupled to a tank circuit consisting of a high-Q coil in parallel with the cyclotron accelerating electrodes. The electrodes or dees act as the capacitor of the resonant circuit, and a high voltage is developed across them. Normal operating voltage on the dees is 10–12 kilovolts. The coil and dees are seen in place in the dee box in Figures 4 and 5.

The Dee Box

The dee box or vacuum chamber is the heart of the machine. It houses an ion source, the dees, and the target. The formation of ions, the acceleration of ions, and the nuclear reactions all take place in the dee box (Figure 3).

The ion source. The ion source consists of a spirally-wound tungsten filament. The filament is heated to incandescence by a high-frequency a-c power supply. The high-frequency is used to minimize self-destructive magnetic effects in the spiral filament. Hydrogen gas is introduced at a point near the white-hot filament, whereupon the gas is ionized by collision with electrons emitted from the filament. The stripped hydrogen nuclei are the protons which are subsequently accelerated by the machine. The relative position of the filament in the dee box is shown in Figure 5.

The dees. The dees are two hollow electrodes which are shaped like the letter "D" (Figs. 3, 4). They are arranged in a plane perpendicular to the magnetic field, and a gap is left between them. The result is similar to a metal pill box split along a diameter. The radio frequency potential is applied between the two dees, and the protons are accelerated by passing out of one dee, through the electric field, and into the second dee. The dees, made of thin sheet copper, are 22.5 cm in diameter, 2.4 cm high, and they are separated by a gap of 1.5 cm. The dees are physically supported by copper "stems" which also serve to carry

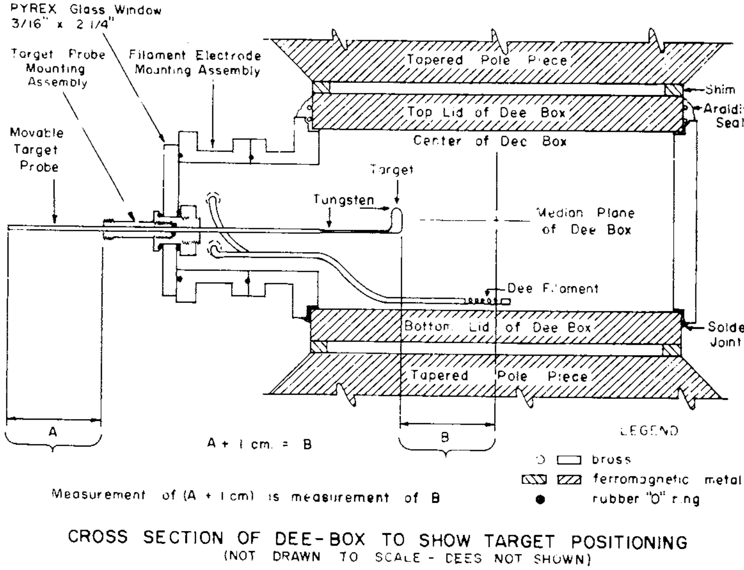

Figure 5. A cross-section of the dee box illustrating the relative positions of the target and the ion source within the box. It also shows the taper, shoulder, and shims of the magnet poles (from Crosland).

electric power and cooling water to the dees. The cooling water is necessary since the r.f. power is dissipated by the dees.

The target. The target is the material sample in which the nuclear reactions take place. It is placed between the dees at a given radius, and when the energetic protons reach the target radius, they collide with nuclei in the target. If the proton energy is high enough, transmutations occur in the nuclei. The protons of the ISU machine have high enough energy to react with several of the light elements. Typical target materials for this machine are lithium, beryllium, carbon, and calcium fluoride.

Performance

The ISU cyclotron presently produces a maximum beam current of about two microamperes. (Beams as high as ten microamperes have been produced.) The two-microampere current corresponds to a proton flux in the order of 10^{13} protons per second. With this number of protons, the nuclear reactions proceed at a high enough rate to be easily studied. It is also a sufficiently high flux to permit the transmutation of C^{12} to the radioactive isotope N^{13} in amounts large enough for accurate half-life determination. Specifications and performance data of the machine are given in Table 1.

Table 1. Specifications of the ISU cyclotron

Size: 10-inch pole diameter
Weight: 2.5 tons exclusive of auxiliaries
Dee voltage: 10,000 to 14,000 volts dee-to-dee
R.F. power: 2,000 watts
R.F. frequency: 25.68 megacycles per second
Magnetic field strength: 17,000 gauss
Projectiles: protons
Maximum energy: 1.5 million electron volts
Beam current: 2 microamperes

Auxiliary Equipment

The ISU cyclotron laboratory has several pieces of auxiliary equipment which are not usually found in a small laboratory. Three of the most valuable pieces of equipment are a scintillation spectrometer, a high precision magnetic field regulator, and and a nuclear resonance field strength meter.

The Scintillation Spectrometer

The scintillation spectrometer is used to study the various decay modes of the radioactive products of the cyclotron. It uses a three-inch sodium iodide crystal to detect the beta and gamma radiation. Energy discrimination circuits enable the experimenter to determine the energy of the radiation, and a scaler is used to indicate the relative intensity of the radiation at each energy level. A plot can be made of number of counts per minute versus energy; and from this plot the energy of the radiation incident on the crystal can be found.

The Magnet Regulator

The high precision magnet regulator is a valuable adjunct to the cyclotron. Since the resonance condition between the frequency of the r.f. power supply and the strength of the magnetic field is a very critical one (8, 9), the magnetic field strength must be maintained at a constant value. The ISU cyclotron magnet is stabilized by regulation of the current to the magnet coils. In the present system, the magnet current is sampled by reading the voltage developed across a precision shunt in series with the magnet coils. This voltage is fed to a difference amplifier where it is compared to a constant reference voltage. The reference voltage is adjusted to correspond to the desired magnet current. If the magnet current is not at the desired level, there will be a difference between the two voltages. The difference voltage controls a transistorized output amplifier stage which, in turn, controls the excitation current to the field of one of the motor-generator sets. This regulation system is capable of holding the 17,000 gauss field to within ± 4 gauss of its nominal value.

Nuclear Resonance Field Strength Meter

For experiments in beam characteristics of the cyclotron it is necessary to know the magnetic field strength to a high degree of accuracy. To achieve high-accuracy field determinations an instrument operating on the principle of nuclear magnetic resonance is used. A sample of powdered lithium is placed in the magnetic field. The lithium nucleus has a magnetic moment, and it will begin to precess in the magnetic field much as the angular momentum vector of a gyroscope precesses in the earth's gravitational field. The precession frequency of the nucleus is proportional to the magnetic field strength. An external oscillator produces a small rotating magnetic field in the lithium sample, and when the frequency of the external oscillator is the same as the precession frequency of the nucleus, the nucleus will absorb a small amount of energy from the field produced by the oscillator. The oscillator frequency at which the change is detected may be used to calculate the magnetic field. The instrument may be read easily to one gauss accuracy.

Acknowledgements

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References

1. The original group was led by Clark M. Varnum of Tama, Iowa, without whose energy and skill the machine would never have been completed. Others in the group were Michael Buck, Ames; Lyle Taylor, Paton; Robert Anderson, Omaha; Richey Scott, Davenport; Howard Shanks, Mason City; LeRoy Humpal, Amana; Delbert Wright, Sanborn Stanley Buss, LeMars; Donald Wolfe, Clinton; and Stanley Christensen, Ames.
2. Major contributors were Bethlehem Steel Company, Collins Radio Company, Radio Corporation of America, Northwestern Bell Telephone Company of Ames, and Ampex Electronic Corporation.
3. Wouters, L. 1949. General recommendations for design of small cyclotrons. Report UCRL 476 of the U. S. Atomic Energy Commission. This article describes a 6-inch cyclotron built by El Cerrito High School in California in some detail. See also Scientific American, 189, p. 154, 1953, for a description of this cyclotron.
4. The Hughes Aircraft Company will now build small cyclotrons to order. One such machine has been installed at Pomona College.
5. Mann, W. B. 1953. The Cyclotron. John Wiley and Sons, New York.
6. Nahmias, M. E. 1945. Machines atomiques, cyclotron et autres accelerateurs. Paris, France.
7. Crosland, R. T. 1959. The use of a 1.5 Mev cyclotron in undergraduate physics instruction. M. S. Thesis, Iowa State University, unpublished.
8. Mueller, A. H. 1961. Proc. Iowa Acad. Sci. 68.
9. Burns, R. R. 1961. Proc. Iowa Acad. Sci. 68.
10. A history of the development of the cyclotron is found in Physics Today 12: 18. October, 1959.