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INTRODUCTION

Since the pioneering work around 1930 that led to the disintegration of atomic nuclei by accelerated ions, much effort has been expended on the development of particle accelerators. The primary objective of this development has always been the acceleration of electrons, protons, deuterons, and α particles to higher and higher energies. Recent progress in the acceleration of these particles to high energies has been reviewed by Judd (1).

Until recently relatively little work was done on the acceleration of ions heavier than helium. In 1940 Alvarez reported the acceleration of six-times-ionized carbon ions to an energy of 50 Mev in the 37-inch cyclotron at Berkeley (2). Further work with the 60-inch cyclotron at Berkeley led, in 1950, to the detection of nuclear reactions produced with carbon ions by Miller, Hamilton, Putnam, Haymond, & Rossi (3). Soon afterwards, the usefulness of accelerated carbon ions for the production of transuranic elements was demonstrated by Ghiorso, Thompson, Street, & Seaborg (4), and a paper pointing out the possibilities of nuclear research with accelerated heavy ions was published by Breit, Hull, & Gluckstern (5). The interest in research with heavy ions created by this work led to the acceleration of heavy ions with other cyclotrons that were designed for deuterons, and the construction of machines designed specifically for the acceleration of heavy ions. Carbon ions with an energy as high as 1.1 Bev have been produced in the fm cyclotron at Chicago (6). However, the emphasis has been on the production of ions with energies of 10 Mev/A or less for use in low-energy nuclear physics experiments.[1]

Review articles describing recent nuclear research with accelerated heavy ions have been published by Breit (7), Flerov (8), Fremlin (9), and Zucker (10). A detailed discussion of much of the recent work was presented at the Second Conference on Reactions Between Complex Nuclei (11). In addition to their employment in nuclear research, accelerated heavy ions are also being used in biological studies (12).

The accelerator required for heavy ions is quite large if singly ionized ions are used. For example, a cyclotron that accelerates singly charged neon ions to 10 Mev/A would have a least 360-in.-diameter poles. A large reduction in the size of the accelerators results from the use of multiply charged ions. However, the higher the state of ionization of the ions, the more difficult it is to get a large beam from an ion source. Therefore, in some machines the ions are accelerated to a moderate energy in a low charge state and then stripped to a higher charge state by being passed through a thin layer of matter. The ion sources used for multiply charged ions and the techniques of electron stripping are discussed in the next sections before the various types of heavy ion accelerators are described.

ION SOURCES

Arc Discharge Sources

During the early experiments on the acceleration of heavy ions at Berkeley, spark-type ion sources similar to those used in spectroscopy were tried (13), and a source of this type has been used on the heavy-ion linac at Kharkov (14). However, for ions of elements available in gaseous form, larger beams are produced by arc-type sources, and this type is used in most heavy-ion accelerators.

To produce ions in a given charge state, the electrons in the arc discharge must have an energy greater than the ionization potential of the electrons to be removed from the ion. The cross section for ionization reaches a maximum when the energy of the electrons in the discharge is three to five times the ionization potential. The ionization potentials of the ions commonly used in heavy-ion accelerators are listed in Table I. It is seen, for example, that the ionization potential for Ne^{+5} is about ten times that for hydrogen, while for Ne^{+10} the ratio is 100. The commonly used proton sources operate with rather low arc voltages and are not suitable for the production of multiply charged ions. Therefore special arcs that operate with high arc voltages have been developed for this purpose.

The most successful sources of multiply charged ions use a dc discharge that is collimated by a magnetic field. The ionizing electrons make multiple traversals through the discharge as in a Penning or Phillips ionization gage (PIG). Figure 1 is a sketch of the source developed for the cyclotron at Moscow by Morozov, Makov, & Ioffe, (15). One of the cathodes is heated by electron bombardment and emits thermionic electrons. With an arc voltage of 750 to 800 v. and arc currents of 4 to 5 amp., beams of 0.1 m. amp. of N^{+5} and 2 m. amp. of N^{+4} are produced. A similar source was built recently by Papeneau, Benezech, & Maillard (15a).

Sources of this type that depend on secondary emission of electrons from cold cathodes to sustain the discharge were developed for the Oak Ridge 63-inch cyclotron by Jones & Zucker (16) and for the heavy-ion linear accelerators at Berkeley and Yale by Anderson & Ehlers (17). The Oak Ridge source produces several m. amp. of N^{+3} with an arc voltage of 600 v. and 3 to 5 amp. of arc current. The Berkeley - Yale source operates with 1 kv. arc drop and 1.5 amp. arc current, and produces m. amp. beams of many ions in the He - Ne mass region with $e/m > 0.15$.[2]

Jones & Zucker also developed a source using a hot filament (16, 18). In this source the lower cathode in Figure 1 is omitted, and the electrons emitted by the filament are used to sustain the discharge. The upper cathode is allowed to float instead of being held at a fixed negative potential. With 250 v. of arc voltage and 3.5 amp. arc current this source produces a few m. amp. of N^{+3} ions.

Figure 2 shows how the number of argon ions produced in various charge states by the Berkeley source depends on the arc current. Similar curves were obtained for nitrogen ions by Morozov, Makov, & Ioffe (15). The rapid increase in the yield of ions in higher charge states with higher arc current suggests that several ionizing collisions are involved in the formation of multiply charged ions, and that single collisions in which several electrons are removed are relatively unimportant.

The fraction of the ions in higher charge states is also increased by lowering the pressure in the discharge. Curves showing this effect have been published by Morozov, Makov, & Ioffe (15). The processes responsible for this effect seem to be the capture of electrons in collisions with neutral gas atoms in the discharge chamber and the change in mean free path (and therefore the energy) of the ionizing electrons. It is difficult to determine the gas pressure in the discharge chamber, but estimates indicate that it is of the order of one micron with the gas consumption in the operating region of about one cc./min. (at atmospheric pressure). The high gas flow used by these sources and the low pressure needed in the region outside the source to prevent capture of electrons by the multiply charged ions mean that high-speed vacuum pumping is required.

The ions are extracted radially through a slit in the side of the anode. Ions from the slit are accelerated by the extractor electrode. In cyclotrons, the extractor is mounted on the dee and the rf voltage on the dee is used for extraction of ions from the source. In the linear accelerators at Berkeley and Yale, a dc voltage of about 15 kv. is applied to the extractor electrode.

PIG discharges have also been used for proton sources for linear accelerators (19). In these sources, the protons are extracted in the axial direction through a hole in a cathode. In preliminary experiments this type of extraction of heavy ions at Berkeley and Manchester did not yield as favorable a ratio of multiply charged ions to singly charged ions as the sources using radial extraction. Radial extraction also has the advantage that the magnet used to collimate the PIG discharge separates the ions to be accelerated from the ions in other charge states. Elimination of ions with the wrong charge reduces the space-charge defocusing in the accelerating column of the dc injector accelerator. However, radial extraction has the disadvantage that the beam is astigmatic.

As in all types of ion sources good performance depends on a number of details, many of which are not clearly understood. For instance, Anderson & Ehlers tried many different cathode materials and chose tantalum and titanium as the best. Jones & Zucker also used tantalum, but Morozov et al. used tungsten in the heated cathode and molybdenum in the cold one. For elements available in the gaseous state only in compounds, different compounds give different performances. Compounds that work well for some commonly used ions are BF_3 for boron and fluorine ions, CO_2 for carbon ions, and H_2S for sulfur ions.

In linear accelerators where the rf accelerating fields are pulsed with a duty factor of about 3 per cent, the life of the source is increased by pulsing the arc discharge. The problems encountered in pulsed operation and their solutions are described by Anderson & Ehlers (17).

A different type of arc discharge, similar to the duoplasmatrons that are coming into wide use as proton sources, has been used by von Ardenne to produce multiply charged ions (20). In operation with an arc drop of 750 v., 0.95 m. amp. of N^{+3} and 0.06 m. amp. of N^{+4} ions were obtained during a 10-μsec. pulse. These yields are not quite as large as those obtained from the PIG sources, and the use of this type of source in a heavy-ion accelerator has not been reported.

Sources for Ions of Solid Materials

In the PIG discharge sources of the type shown in Figure 1, bombardment of the cathodes by ions in the discharge causes the cathode material to be sputtered away. Ions of the sputtered cathode material are observed in the beam extracted from the source. For most materials the beam currents obtained are too small to be useful. However, Anderson has used this method to obtain 1-m. amp. beams of singly charged ^{6}Li and 0.1 m. amp. of doubly charged ^{6}Li from the ion source at Yale (21). The lithium was loaded into a pocket in the lower titanium cathode and the source was operated in the usual way, using nitrogen as to sustain the discharge. Boron nitride insulators were used in the source since they are not damaged by lithium vapor. The $^{6}Li^{+1}_{1}$ ions have a high enough e/m to be accepted by the Yale linear accelerator.

A 0.5-μ amp. beam of singly charged lithium ions has been obtained from a standard rf ion source by Cornides, Roósz, & Siegler (22). The rf discharge was produced in hydrogen, and then lithium was introduced from a heated tube on the side of the discharge chamber.

When certain lithium compounds are heated to temperatures over 1000 °C, singly charged lithium ions are emitted. This phenomenon has been used for many years to make lithium ion sources. Recently, using a source of this type, Norbeck obtained 5 to 10 μ amp. of lithium ions from an electrostatic accelerator (23). A powder of the mineral β-eucriptite, a lithium-aluminum silicate eutectic mixture, was suspended in amyl acetate and painted onto a filament.

The methods used to produce lithium ions can also be used for heavier alkali metals, but the charge on the ions is too small for them to be used in resonance accelerators.

ELECTRON STRIPPING

Equilibrium Charge Distribution

When fast ions pass through matter, they lose and capture electrons in collisions with atoms of the material they are going through. The way in which a beam of 8.7-Mev O^{+3} ions changes charge while passing through argon is illustrated in Figure 2. The distribution of the ions among the various charge states changes until equilibrium is established between capture and loss of electrons. After the ions have gone through enough stripping material to establish equilibrium, no further change in the charge-state distribution occurs as they pass through more material. Equilibrium is reached before any significant degradation of the energy or multiple scattering of the ions takes place.

The ratio of the capture and loss cross sections for a given electron depends on the orbital velocity of the electron within the ion and the velocity of the ion. The electron-loss cross sections are greater than the capture cross sections if the ion velocity is larger than the orbital electron velocity, and vice versa. If the ion velocity equals the orbital velocity of a given electron, the capture and loss cross sections are nearly equal, and at equilibrium some of the ions will carry this electron and some will not. Using an approximate form of the Fermi-Thomas distribution of orbital electron velocities, Bohr obtained the formula $\bar{e}/Z = v/v_0 Z^{2/3}$ for the average charge $\bar{e}$ carried by a beam of ions at equilibrium (25). In this equation, v is the ion velocity, v_0 is the velocity of the electron in the ground state of hydrogen, and Z is the atomic number of the ion.

For ions in the mass region carbon to neon, Bohr's formula gives values of $\bar{e}$ that are too high, especially for highly ionized ions. Brunings, Knipp, & Teller (26) have used two methods for determining the appropriate orbital electron velocities and obtained more complicated relations between $\bar{e}/Z$ and $v/Z^{2/3}$. An empirical-empirical relation between $\bar{e}/Z$ and $v/Z^{2/3}$ was obtained from experimental equilibrium charge distributions by Papineau (27). Papineau's curve, extended to higher energies with the data of Heckman, Hubbard, Perkins, & Simon (28), is plotted in Figure 3, with the energy per nucleon in the abscissa.

For many light ions, the ratio e/m which determines the parameters of the accelerator is equal to half the ratio e/Z. For these ions, the energy per nucleon required for stripping to a given e/m increases as $Z^{4/3}$. For heavier ions, in which e/m becomes less than half e/Z, the stripping energy increases as a slightly higher power of Z. At a given velocity $\bar{e}/m$ decreases with the mass of the ion. Therefore, the choice of the velocity at which stripping is done in an accelerator can be optimum for only one ion. For lighter ions, the accelerator is larger than is necessary and for heavier ions a large fraction of the beam is not stripped to a high enough e/m and is lost.

As shown in Figure 2, most of the stripped beam is distributed over three charge states. As a result, some loss of beam occurs unless the section of the accelerator that follows the stripper accepts the beam in more than one charge state. and unless the lowest charge accepted is one charge lower than the average charge.

There is some evidence that the average equilibrium charge $\bar{e}$ is slightly higher for solid stripper materials than for gaseous ones (29, 30). According to Bohr and Lindhard (31), stripping should be more probable in solid materials because many of the electrons of the ion are in excited states, whereas in gases there is sufficient time between collisions for the ions to return to the ground state. There are also some indications of a slight dependence of $\bar{e}$ on the atomic number of the stripper material. However, the dependence of $\bar{e}$ on the stripper material is not large enough to be important in the choice of a material to be used in a stripper for an accelerator.

The experimental equilibrium charge distributions determine only the ratios of the capture and loss cross sections. In order to determine the thickness of stripper material required, it is necessary to know the absolute values of the cross sections. The absolute cross sections can be determined from measurements of the charge distributions under nonequilibrium conditions. However, only a few scattered experiments of this type have been performed (24, 32, 33).

Cross sections for capture and loss of electrons by oxygen, neon, phosphorus, and argon ions passing through argon have been calculated by Gluckstern in the energy range from 0.2 to 1.2 Mev/A (34). The calculated loss cross sections are in good agreement with experiment, but the capture cross sections are too high. The theory does not consider collisions in which more than one electron is exchanged, although Gluckstern suggests that these may be significant. To determine the thickness of stripper material needed, one can use the velocity dependence of the cross sections obtained by Gluckstern together with the experimental measurements available and get a fair estimate. For ions in the nitrogen-to-neon region with 1 Mev/A, about 10 $\mu g/cm.^2$ of stripper material is sufficient.

Foil Strippers

A stripper 10 μg./cm.^{2} thick introduces an energy spread of the order of 10^{-5} Mev/A, and the rms multiple scattering angle is of the order of 0.1 degree. These values are considerably smaller than the acceptance limits of an accelerator following the stripper. However, if the stripper is more than 100 μg./cm.^{2} thick, the multiple scattering angle begins to be an appreciable fraction of the angular acceptance.

Although in principle a foil is the simplest kind of stripper one can use, some difficulty is involved in making foils less than 100 μg./cm.^{2} thick that will stand up in an intense beam of ions. However, several laboratories have succeeded in producing suitable foils and are using them for strippers in accelerators.

Nickel foils 45 μg./cm.^{2} (500 A) thick are available commercially from the Chromium Corporation of America(35). The nickel is electrodeposited on a 0.1-mil copper backing which can be removed with activated chromic acid. Nickel foils of this type were used at first on the Yale heavy-ion accelerator, but they were later abandoned in favor of aluminum oxide foils.

Aluminum oxide foils are prepared by anodizing a thin sheet of aluminum (36). The oxide coating is removed from one side of the anodized sheet with NaOH, and then the excess aluminum is removed with HCl. Foils with thickness from 25 to 250 μg./cm.^{2} (700 to 7000 A) can be prepared this way. The thickness of the oxide layer is determined by the anodization voltage and is independent of the electrolytic concentration. Aluminum-oxide foils 40 μg./cm.^{2} thick stand up for weeks in the Yale accelerator.

Carbon foils from 4 μg./cm.^{2} to 1 mg./cm.^{2} (200 A to 5μ) thick can be prepared by evaporating carbon from a carbon arc. The carbon is evaporated onto a glass plate and then the film is floated off on water. Carbon foils 5 μg./cm.^{2} thick used for stripping in the Harwell tandem electrostatic accelerator stand up in the beam almost indefinitely (37).

Gas Strippers

A gas-filled chamber with an opening in each end and a differential pumping system has been used in many studies of the capture and loss of electrons. A gas-filled tube was used by Bittner to strip a beam of 400-kev. He^{+1} ions inside the high-voltage terminal of a Van de Graaff generator (38), and a system of this type is used for stripping in the tandem Van de Graaff accelerators at Chalk River and Aldermaston.

To reach equilibrium in a gas-filled tube 20 inches long, a pressure of about 50 μ is required at the center of the tube. In a system where axial length is not limited or where a small-diameter tube can be used, a differential pumping system is feasible. However, in a linac, where the axial length available is limited by phase debunching of the beam and the diameter of the beam tube is about half an inch, the differential pumping problem is severe, and systems of this type have not been used.

Jet Strippers

Stripping can also be done with a supersonic jet of gas directed transversely to the beam direction. If a jet of a condensable vapor is used, the problem of pumping out the gas introduced can be eliminated by collecting it on a cold trap. A jet of carbon dioxide was used to strip a beam of He^{+1} ions from a Van de Graaff accelerator by Geller & Prevot (39). The carbon dioxide was solidified in the cold trap.

The heavy-ion linac (Hilac) at Berkeley uses a jet of mercury similar to the one developed by Beringer & Rall (40). The mercury vapor is supplied to the jet nozzle from a boiler and then condensed to a liquid and returned to the boiler. For surface densities, in the jet, of 10 μg./cm.^{2} the boiler pressure is about 50 mm. Hg, while the vacuum chamber surrounding the jet is at 10^{-5} mm. Hg. With a pressure drop this large, the jet is underexpanded for any practical nozzle design, and the jet expands into the low-pressure region. Therefore, it is necessary to put cold traps around the beam tube near the jet to prevent mercury from streaming into the linac cavities. Diffusion pump oil could be used in this type of jet; however, in linacs any oil that gets onto the drift tube surfaces increases the tendency to spark.

dc HIGH-VOLTAGE ACCELERATORS

Conventional dc Accelerators

The standard dc high-voltage accelerators that have been in use for many years accelerate any ion in any charge state. At Chicago, Minnesota, and Saclay, Li^{+1} ions accelerated in machines of this type are being used to study nuclear reactions with very light targets. The only unusual feature of these accelerators is the ion source discussed above.

For ions heavier than lithium, the energy is too low for the study of nuclear reactions unless multiply charged ions are used. In principle, it would be possible to use one of the special sources for multiply charged ions. In a 6-Mv. Van de Graaff generator, ions with charge +5 would be accelerated to 30 Mev. However, the sources for multiply charged ions require more power and more space than is customarily available in such a machine. Moreover, these sources need frequent maintenance, which would be inconvenient for a source located in a pressure vessel. For these reasons, the use of the standard dc machines for ions heavier than lithium has been very limited.

Tandem Van de Graaff Accelerators

When a very-low-energy beam of atomic ions passes through matter, many of the ions capture electrons. Most of the ions in the equilibrium charge distribution are neutral, but a few of them carry a negative charge. Also, when a beam of molecular ions is dissociated by being passed through matter, some of the atomic ions formed are negative. Negative ions formed in either of these processes can be accelerated from ground to the positive high-voltage terminal of a dc accelerator. In the high-voltage terminal, electrons can be stripped off and the resultant positive ions accelerated from the terminal back to ground.

This type of accelerator was first suggested by Bennett in 1937 (41), but little interest in the idea developed until the possibilities were pointed out again by Alvarez in 1951 (42). The first Van de Graaff accelerator using this principle was built by the High Voltage Engineering Corporation for the laboratory at Chalk River (43). Recently, other machines of this design were put into operation at Florida State University and the University of Wisconsin. Similar accelerators built by Metropolitan-Vickers are in use at Aldermaston and at Harwell (44). Several more machines of this type, now known as "tandem" Van de Graaff accelerators, are being built.

One of the advantages of the tandem Van de Graaff over the conventional ones is that the ion source and its associated equipment are at ground potential where there is no limitation on the space or power available.

An ion source that produces 25 μ amp. of negative ions was developed by Weinman and Cameron (45). Positive ions are produced in a PIG discharge using a hot filament and axial extraction. The extractor electrode is a tube with hydrogen introduced into the center of it. About 2 per cent of the positive ions extracted at 10 kev. are converted to negative ions. The yield of negative ions from dissociation of molecular ions turned out to be larger than the yield from capture by atomic ions. Fogel, Koval, & Timofeev used a similar ion source with a mercury jet and obtained 40 μ amp. of O^{-1} ions (46). The British machines use an rf source developed by Collins & Riviere (47). The negative ions are produced by introducing gas into the exit canal. The Chalk River machine also uses an rf source.

The negative ions are magnetically separated from other components of the ion source beam and accelerated to an energy of from 40 to 120 kev. before entering the accelerating column of the Van de Graaff. In the machines that use gas strippers in the high-voltage terminal, the gas is pumped down the high-energy accelerating column to avoid stripping the negative ions in the low-energy column.

To date, oxygen ions have been used for most of the heavy-ion work with tandem accelerators. However, carbon ions have also been accelerated at Chalk River, and it is expected that a large variety of ions will eventually become available. In a 6-Mv. tandem Van de Graaff accelerator, a large fraction of the negative oxygen ions are stripped to the +5 charge state in the high-voltage terminal, and the final energy is 36 Mev. For energies below 36 Mev, the tandem Van de Graaff accelerators have the advantages over resonance accelerators of continuously variable energy and precision energy control. Beam currents of a few tenths of a μamp. are available with a 1/16-in. diameter.

A further extension of the tandem scheme that uses two high-voltage generators, one positive and one negative, is now under development. The negative ion source is mounted in the negative high-voltage terminal. The negative ions are accelerated to ground, then to the positive high-voltage terminal, where they are stripped, and then to ground again. With 6 Mv. on each terminal, the ions would have 12 Mev. at the stripper, and a good yield of O^{-6} ions should be obtained. The final energy of the oxygen ions would be 48 Mev. or 3 Mev./A.

CYCLOTRONS

Cyclotrons using Stripping

The rf frequency for many fixed-frequency cyclotrons is chosen for the acceleration of deuterons and α particles which have an e/m of 1/2. Completely stripped ions of ^{12}C, ^{14}N, ^{16}O, and ^{20}Ne also have an e/m of 1/2 and can be accelerated in these machines. Completely stripped ions of ^{12}C were used in the early cyclotron experiments of Alvarez (2), Tobias (48, 49), and Condit (50, 51). The ion sources in use at that time operated with an arc voltage of 200 volts. As seen in Table I, the electrons in the arc were well below the ionization potential for the sixth electron in carbon. Tobias suggested that the completely stripped ions were produced by high-energy electrons that oscillate between the dees.

When further ion source development (13) still did not yield enough external carbon beam to permit detection of nuclear reactions, bombardments using the internal circulating beam were tried. Not only were nuclear trans-mutations detected, but also the yield indicated that the circulating beam of carbon ions was 10^3 to 10^4 times greater than the external beam (52). The ratio of circulating beam to external beam for light ions such as deuterons was about 10 to 1 at that time. The reason for the low efficiency of the deflector for C^{+6} ions turned out to be a large spread in the energy at the deflector radius. The intensity of the C^{+6} beam increased rapidly for lower energies, and only the high-energy tail of the energy distribution received the right amount of deflection in order to go through the external beam channel.

The early experiments of Condit (50, 51) had established the existence of a C^{+2} beam accelerated with the third harmonic of the orbital frequency of the ions equal to the cyclotron rf frequency. Further experiments led to the conclusion that the C^{+6} ions were formed from C^{+2} ions that were pre-accelerated by harmonic acceleration and stripped in collisions with residual gas atoms in the cyclotron tank (52). After an electron has been lost the center of curvature of the ion's orbit would not be at the center of the cyclotron, and the orbital motion would not be synchronized with the dee voltage. As the ions crossed the dee gaps they would sometimes be accelerated and sometimes decelerated. Some of the ions would undergo further collisions while their energy was high enough to produce C^{+6} ions. Some of the C^{+6} ions formed in this way would be accelerated to full radius, but ions formed at different points in the cyclotron would have orbits with different centers of curvature and reach a given radius with different energies. Subsequent experiments with the acceleration of heavy ions in the 60-inch cyclotron at Birmingham by Walker, Fremlin, Link, & Stephens (53, 54) support this explanation of the production of high-energy C^{+6} ions. It is possible, however, that the high-energy electrons between the dees are significant in the stripping process.

This method of accelerating heavy ions in cyclotrons designed for deuterons has also been used at Stockholm (55) and Saclay (56). Further work at Berkeley resulted in internal beams of 0.2 μ amp. of carbon ions with energy greater than 100 Mev. and an external beam of 0.001 μa of 120-Mev carbon ions (57). By increasing the magnetic field of these cyclotrons above the design values, smaller beams of high-energy N^{+6}, O^{+6}, and Ne^{+6} ions have been obtained.

At full radius, the intensity of the 1-Mev./A beam of doubly charged ions is about 500 times the intensity of the high-energy +6 beam, and the heating of internal targets by it is a serious problem. The large energy spread in the internal beam makes it impossible to do precise experiments, and the external beams are too small for most experiments. For these reasons, this method of accelerating heavy ions has largely been abandoned since the advent of accelerators designed specifically for heavy ions.

Cyclotrons Without Stripping

Since no method for stripping in a controlled manner in a cyclotron has yet been developed, several laboratories have built cyclotrons that accelerate multiply charged ions obtained directly from the ion source. After leaving the source, the ions are accelerated in the conventional manner.

The 120-cm. cyclotron at the Physical-Technical Institute in Leningrad (58) and the 63-in. cyclotron at Oak Ridge (59) have accelerated triply charged nitrogen ions for some time. At

Leningrad 0.5 μamp. of 16-Mev N^{+3} ions is obtained on a 3-mm.-diameter external target. At Oak Ridge the energy of the external beam is 28 Mev and the current is 2 μamp. Recently, quadruply charged ions of carbon, nitrogen, oxygen, and neon have been accelerated in the Leningrad cyclotron (60). Energies up to 40 Mev are obtained, and the external beam current varies from 10^{-9} to 3×10^{-7} amp. These machines have proved very useful for the study of Coulomb and nuclear interactions with light elements.

At the Atomic Energy Institute in Moscow, the ion source developed by Morozov, Makov, and Ioffe (15) has been used with a 150-cm. cyclotron to accelerate N^{+5} ions to 110 Mev, or 7.8 Mev./A (8). A circulating beam of 1 μamp. is obtained, but an external beam has not been reported. C^{+4} and O^{+6} have also been accelerated to 8 Mev./A. This machine has been used for many studies of nuclear reactions with heavy targets, but the necessity of using the internal beam has limited the complexity of the experiments. The Moscow group has recently moved to Dubna, where they are building a very large cyclotron designed to produce large currents of carbon, nitrogen, and oxygen ions with energies of 12 Mev./A.

Advances in cyclotron technology made in the last few years have led to the initiation of several projects to build cyclotrons that can be used to accelerate heavy ions with energies up to 100 Mev./A. The development of cyclotron rf systems whose frequency can be varied over a wide range, and of magnets whose field can be varied between wide limits, allows the acceleration of ions with a wide variety of e/m values. Also, the energy of the ions at the entrance to the deflector channel can be varied to obtain a variable-energy external beam. The use of azimuthally varying magnetic fields allows these machines to be used also for the acceleration of light ions to relativistic energies without frequency modulation and the resultant loss in beam intensity. Very versatile cyclotrons of this type with pole diameters of 76 inches and 88 inches are nearing completion at Oak Ridge and Berkeley, respectively. A detailed account of these and many other new cyclotrons is given in the proceedings of the Conference on Sector-Focussed Cyclotrons (61).

LINEAR ACCELERATORS

Introduction

Standing-wave linear accelerators of the type Alvarez developed for protons (62) have several advantages over cyclotrons for the acceleration of heavy ions. The size and complexity of the ion source is not as restricted. Stripping can be used without the large loss in intensity and the large energy spread that occur with stripping in a cyclotron. It is easier to obtain a well-focused mono-energetic external beam. Ions with different e/m can be accelerated by changing only the rf voltage, whereas in a cyclotron a variable-frequency rf system or a magnet that retains the proper field shape at different field strengths is required to accomplish this.

Very similar linear accelerators that produce beams of heavy ions with 10 Mev/A are in operation at Berkeley and at Yale University (63), and a somewhat different machine is operating at the Physical-Technical Institute in Kharkov (14). The injection system for a fourth heavy-ion linac is operating at Manchester and the main part of the linac is under construction.

rf Cavities

The main part of these linear accelerators consists of a long cylindrical cavity resonator. Ions are injected into the main cavity with an e/m of about 0.3 and energy of about 1 Mev/A. The length of the cavity required for energies of 10 Mev/A depends on the accelerating electric field that can be achieved without sparking, as well as the e/m of the ions. The sparking limit depends somewhat on the frequency of the rf fields. In the 70-Mc. machines at Berkeley, Yale, and Manchester, the design value of the average electric field over the length of the cavity is 0.5 Mv./ft., resulting in a cavity length of 90 ft. The Kharkov machine operates at 140 Mc. with a higher average cavity field and uses a cavity 60 ft. long.

In the Kharkov machine, focusing is done with grids as in the early proton linacs. However, since this accelerator has 101 drift tubes, the beam loss from interception by the grids is considerable. Because of the lower frequency, only 67 drift tubes are used in the main cavity of the Berkeley, Yale, and Manchester linacs. In these machines, interception of the beam by focusing grids is eliminated by the use of alternating-gradient focusing. The focusing fields are provided by quadrupole magnets placed inside the drift tubes. With this focusing system nearly all the beam injected is transmitted.

To achieve the correct value of the accelerating fields at all points in long cavities such as these it is necessary to control the dimensions to very close tolerances or to use a number of tuners. This problem is eased considerably in the Manchester design by dividing the main cavity into two sections each 45 ft. long. Dividing the cavity into sections also has the advantage that a half-energy beam can be obtained merely by turning off the rf field in the second cavity and allowing the beam to drift through it; the quadrupole magnets in the drift tubes of the second cavity can then be used to focus the beam drifting through it, and very little beam is lost in this process.

The main cavity requires 2.5 Mw. of rf power to excite it. The machines are pulsed to reduce the average rf power consumption. The length of the pulses is 400 μsec. at Kharkov and 2 msec. at Berkeley and Yale. The pulse rate is 10 to 15 pulses per second. At Berkeley and Yale the rf power is supplied by four large shielded-grid triodes, while at Kharkov it is supplied by a larger number of smaller tubes.

Injection

Beam is injected into the linac at Kharkov with a 2.5-Mv. Van de Graaff accelerator. The multiply charged ions are formed directly in the ion source. The charge states required are +4 for carbon and nitrogen and +5 for oxygen. These ions are injected into the linac with an energy of 0.7 Mev/A.

In the Berkeley-Yale and the Manchester designs, the ions are accelerated to the injection energy in a lower charge state and then stripped to an e/m of 0.3 or more before being injected into the main cavity of the linac. The large range of allowable synchronous phases resulting from the use of quadrupole focusing magnets in the main cavities permits the simultaneous acceleration of ions in several charge states to the same energy.

At Berkeley and Yale the e/m of the ions before stripping must be at least 0.15. Therefore the ion source is required only to produce doubly charged ions for carbon and lighter ions, and triply charged ions in the region from nitrogen to neon. In the Manchester machine the minimum e/m of the ions from the source is 1/8, and doubly charged ions can be used for ions as heavy as oxygen.

The intense arcs used as sources of multiply charged ions require frequent maintenance work. The use of these sources in a pressure-insulated electrostatic accelerator means that considerable time and effort is required each time access to the source is necessary. For this reason the Berkeley, Yale and Manchester machines use Cockcroft-Walton accelerators, insulated with air at atmospheric pressure, for the first stage of acceleration. The ions are then accelerated with a short section of rf linac to the energy of 1 Mev/A required for stripping and injection into the main linac. This short linac is often referred to as the prestripper linac and the main linac cavity as the poststripper linac.

At Berkeley and Yale the maximum voltage of the Cockcroft-Walton accelerator is 470 kv. and the energy of the ions injected into the prestripper linac is 70 kev./A. At this low imput velocity the drift tubes become very short for the rf frequency of 200 Mc. usually used in proton linacs. The rf fields penetrate into the bore of the drift tubes and the tubes lose their effectiveness for shielding the ions from the fields during the reverse part of the cycle. In addition, the space inside the drift tubes is too small for quadrupole focusing magnets and the magnetic fields required are very high.

At the frequency of 70 Mc. used at Berkeley and Yale, the length of the first drift tube in the prestripper is 1.7 inches. With the 3/4-in. bore used, this length is sufficient to shield the ions from the rf field adequately, and it would be possible to fit a quadrupole magnet inside. However, when these accelerators were designed there was very little experience with alternating-gradient linacs. It was felt that if quadrupole magnets were used for focusing, a larger bore should be used and the radial motion should remain stable for all allowable phases of the ions. Magnetic fields higher than those attainable were required under these conditions. Therefore, focusing grids are used in the prestripper sections of these linacs.

The diameter of the 70-Mc. cavities used in the Berkeley and Yale linacs is 10 ft, and construttion of cavities of the Alvarez type for lower frequencies is unattractive because of the large diameter of the cavities. Considerable work was done on the problem of injection into linacs at 70 kev./A during the development of the high-current linear accelerator at the Lawrence Radiation Laboratory in Livermore (64).

One solution was the use of an Alvarez-type cavity with extra-long drift tubes, so that the ions cross an accelerating gap only once in every two cycles of the rf frequency. In this scheme, plenty of room for the focusing magnets is provided inside the drift tubes, but the loss of accelerating efficiency caused by penetration of the rf fields into the bore region is not improved.

Another solution is to use a lower frequency and to keep the size down by using another type of cavity. In the first section of the high-current linac, the first two drift tubes were mounted on 24-Mc. quarter-wave stubs. In Manchester, the prestripper linac is a 25-Mc. Sloane-Lawrence accelerator. These types of accelerators are not suitable for acceleration of ions to high energy because they require more rf power than the Alvarez type. However, the phase bunching is good enough so that one can use them to inject into a linac of the Alvarez type operating at a frequency that is a multiple of the frequency of the low-energy linac. In the high-current linac the main accelerator cavity operated at twice the frequency of the quarter-wave input section. At Manchester the frequency of the poststripper linac will be three times the frequency of the Sloane-Lawrence prestripper linac. The high voltage of the Cockcroft-Walton injector for this machine is only 200 kv., and the energy of the ions at injection into the prestripper cavity is 25 kev./nucleon.

Performance

The total peak-beam currents during the pulse from the Berkeley and Yale linacs is in the neighborhood of 50 meter μamp. for ions in the boron-to-neon region. For a pulse rate of 15 pulses per second the total-time average beam is 1.7 meter μamp. About half of the total beam can be focused onto a 1/8-in.-diameter spot. Because the multiply charged ions must be formed in the ion source rather than in a stripper, and because of the interception of beam by the large number of focusing grids, the beam current from the machine in Kharkov is somewhat smaller. Work on the installation of a stripper and alternating-gradient focusing on this machine is under way.

Although ions as heavy as argon can be accelerated in the Berkeley and Yale machines, the beam current is lower by a factor of 50 than it is for ions in the boron-to-neon region. The reasons are that the yield of the A^{+6} ions required from the ion source is smaller than the yield of the doubly and triply charged lighter ions, and the velocity at the stripper is too low to strip a large fraction of the argon ions to the +12 charge state required for acceleration in the poststripper linac. Stripping at a higher velocity in these machines would increase the beam interception on the focusing grids in the prestripper linac and result in smaller beams of the ligher ions.

FUTURE POSSIBILITIES

Variable Energy

The tandem Van de Graaff accelerators already offer variable-energy beams in the lower energy region. Cyclotrons that produce variable-energy external beams of light ions have been in operation for several years and the application of the same principles to heavy-ion cyclotrons seems straightforward. It is possible to vary the energy of a linac in discrete steps by dividing it into several separate cavities and turning off the rf power in one or more of the cavities at the output end. In the last cavity of the linac at Manchester, it is planned to install a moveable diaphragm that will cut off the rf field in the output end of the cavity. This system will allow variation of the energy in steps equal to the energy gain in one accelerating gap or about 200 kev./A. A similar proposal is being studied at Berkeley.

Higher Currents

External beam currents of 2 μamp. of 28-Mev N^{+3} ions have been obtained from the 63-inch cyclotron at Oak Ridge. Similar currents at higher energies should be obtained from the larger cyclotrons that are being built. Larger currents could be obtained from a cyclotron by accelerating ions with a lower charge, but for high energies the size of the magnet required makes this approach unattractive.

The high-current linac was not pulsed, and produced time-average beam currents of 200 m. amp. of protons. Although beam currents of heavy ions as large as this do not appear practical with the present technology, the average beam currents from the Berkeley and Yale machines could be increased by a factor of 30 by supplying enough rf power to operate them constant-wave. Operating experience with alternating-gradient linacs obtained during the last few years indicates that it would be possible to put quadrupole magnets in the prestripper cavities of these machines. Elimination of beam loss on the grids should increase the beam transmitted by a factor of about six. Use of higher-voltage dc injectors for linacs, and further exploitation of the techniques of low-velocity rf acceleration used in the high-current linac, would lower the e/m required of the ions from the source and give increased beam currents, especially of ions heavier than neon. These techniques could also be used to accelerate ions that are heavier than argon.

Higher Energies

Acceleration of heavy ions to energies higher than 10 Mev/A in a cyclotron involves the use of a very large and expensive magnet. The extension of linear accelerators to energies of 20 to 30 Mev/A appears straightforward. Above these energies, the linacs become too long and the rf power consumption too high to be very attractive, although use of linac cavities of the Alvarez design appears possible for energies up to a few hundred Mev/A.

The use of a linac to inject fully stripped heavy ions into a cyclotron or synchrotron has been suggested by Tobias (65). The feasibility of building a synchrotron to accelerate heavy ions to energies in the region of 125 Mev/A for use in biophysical research is being studied at Berkeley.

FOOTNOTES

1. The term "heavy ion" as used here refers to any ion heavier than helium, and by most standards the particles now being accelerated in heavy-ion accelerators would be considered light ions. The ions produced by a linear accelerator or a cyclotron with a fixed $H\rho$ all have the same velocity. Therefore the energy of the ions depends on their mass, but the energy per unit mass is the same for all ions. For this reason, the energy per nucleon in the nucleus of the ion (Mev/A) is a unit that is often used in heavy-ion work, rather than the total energy of the ions. When a beam current of multiply charged heavy ions is measured with a Faraday cup, the current reading must be divided by the charge on the ions to obtain a current representing the same number of particles per second as the same current of protons. However, experimenters in this field customarily do not divide by the charge, and the term meter-μamp.is sometimes used to indicate this.

2. In this article the charge-to-mass ratio e/m of the ions is expressed in units of the charge-to-mass ratio of the proton.

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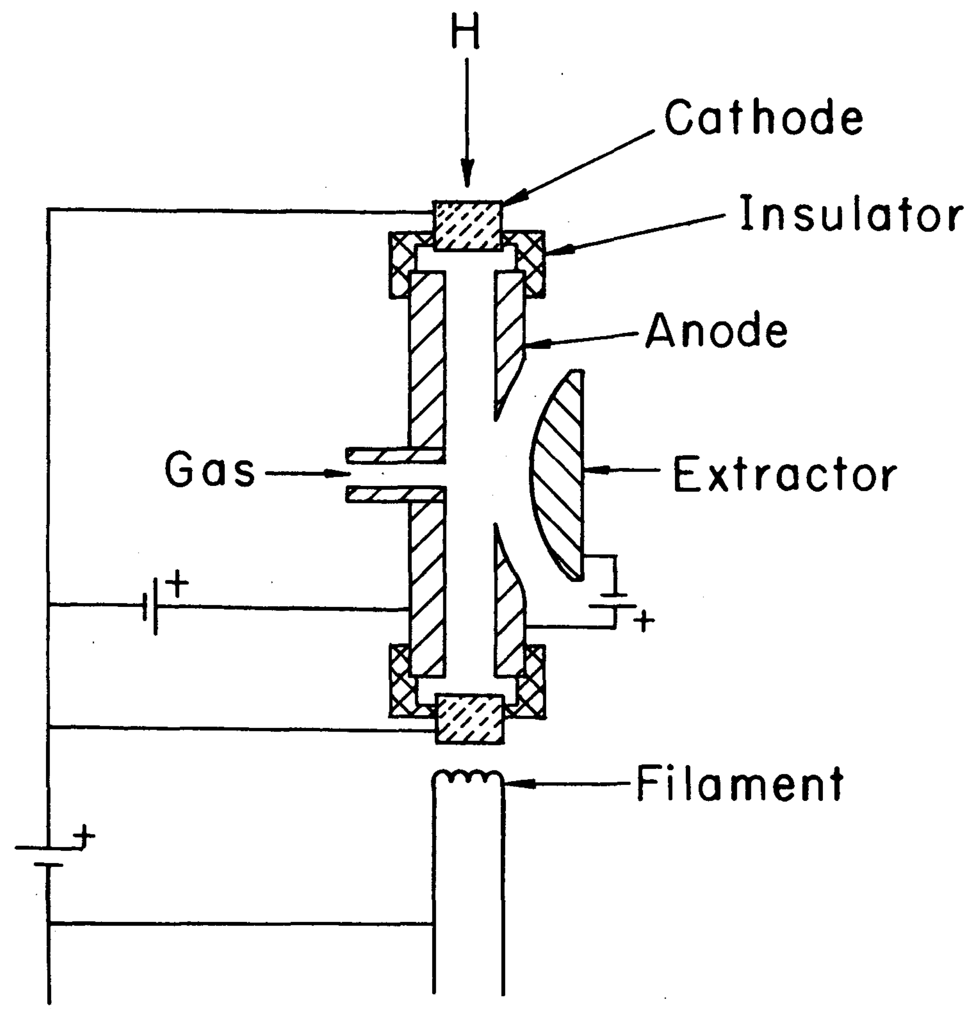
FIGURE LEGENDS

1. Schematic drawing of the PIG-type ion source used in the 150-cm. cyclotron at Moscow (15).
2. Yield of multiply charged argon ions as a function of the arc current. The data were obtained by Gavin, using a constant arc drop of 1000 v. in the Berkeley source.
3. Stripping of a beam of 8.7-Mev O^{+3} ions in argon (24).
4. Dependence of the average equilibrium charge $\bar{e}$ on the energy per nucleon, E/A, of ions of atomic number Z. For comparison, the values given by Bohr's formula are indicated by the dashed curve.

Table I

IONIZATION POTENTIALS (VOLTS)

Charge	H	He	B	C	N	O	F	Ne	Si	S	A
1	13.5	24.5	8.3	11.3	14.5	13.6	17.4	21.6	8.1	10.4	15.8
2		54.1	25.0	24.4	29.6	35.1	35.0	41.1	16.3	23.4	27.6
3			37.8	47.9	47.4	54.9	62.6	63.4	33.5	34.7	40.9
4			258.1	64.5	77.4	77.4	87.2	97.2	45.1	47.3	59.8
5			338.5	392.0	97.9	113.9	114.2	126.4	166.7	72.5	75.0
6				498.8	551.9	138.1	157.1	157.9	205.1	88.0	91.4
7					666.8	739.1	185.1	207.3	246.4	281.0	124.2
8						871.1	935.6	239.0	303.7	328.8	143.5
9							1102	1196	351.0	379.0	422.6
10								1360	401.3	448.6	480.0
11									476.0	506.4	539.5
12									523.2	564.6	621.1
13									2436	651.7	688.5
14									2666	706.4	755.5
15										3220	854.4


H
Cathode
Insulator
Anode
Gas
Extractor
Filament

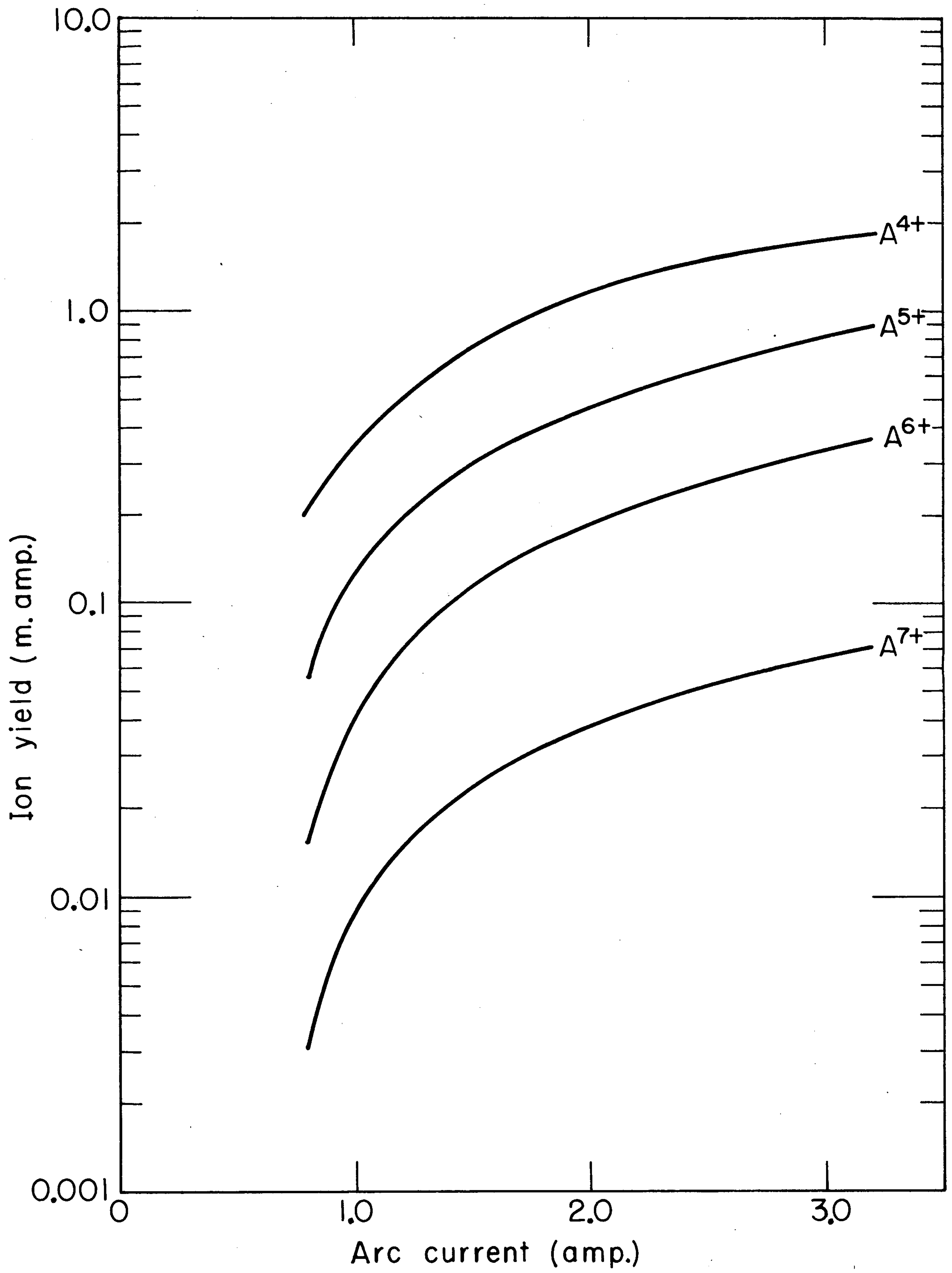

10.0
1.0
0.1
0.01
0.001
0
1.0
2.0
3.0
Ion yield (m. amp.)
Arc current (amp.)
A4+
A5+
A6+
A7+

Fig 2

59360-2

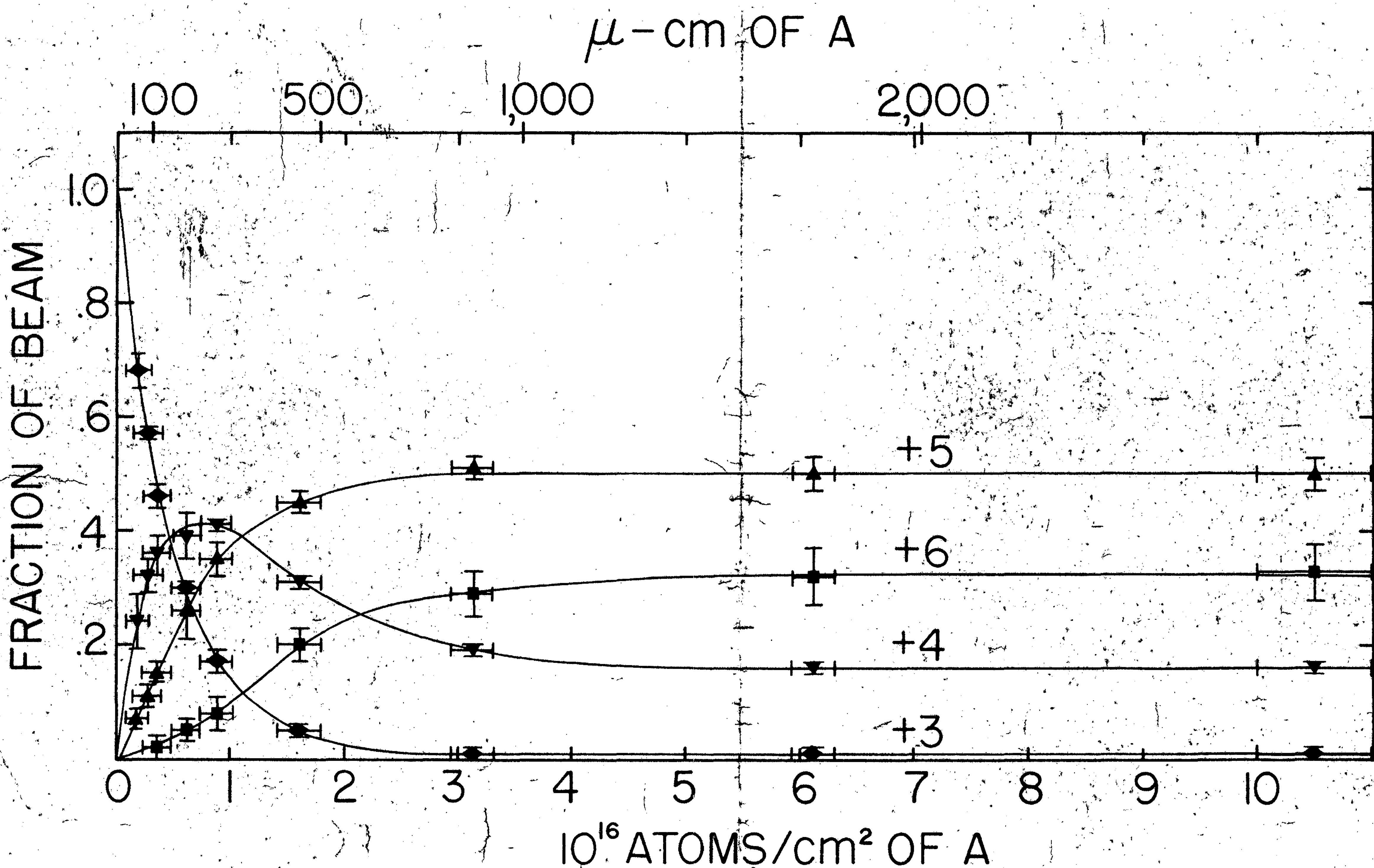

μ-cm OF A
100
500
1,000
2,000
FRACTION OF BEAM
1.0
.8
.6
.4
.2
+5
+6
+4
+3
0
1
2
3
4
5
6
7
8
9
10
10^{16} ATOMS/cm^2 OF A

Fig 3

22822-2

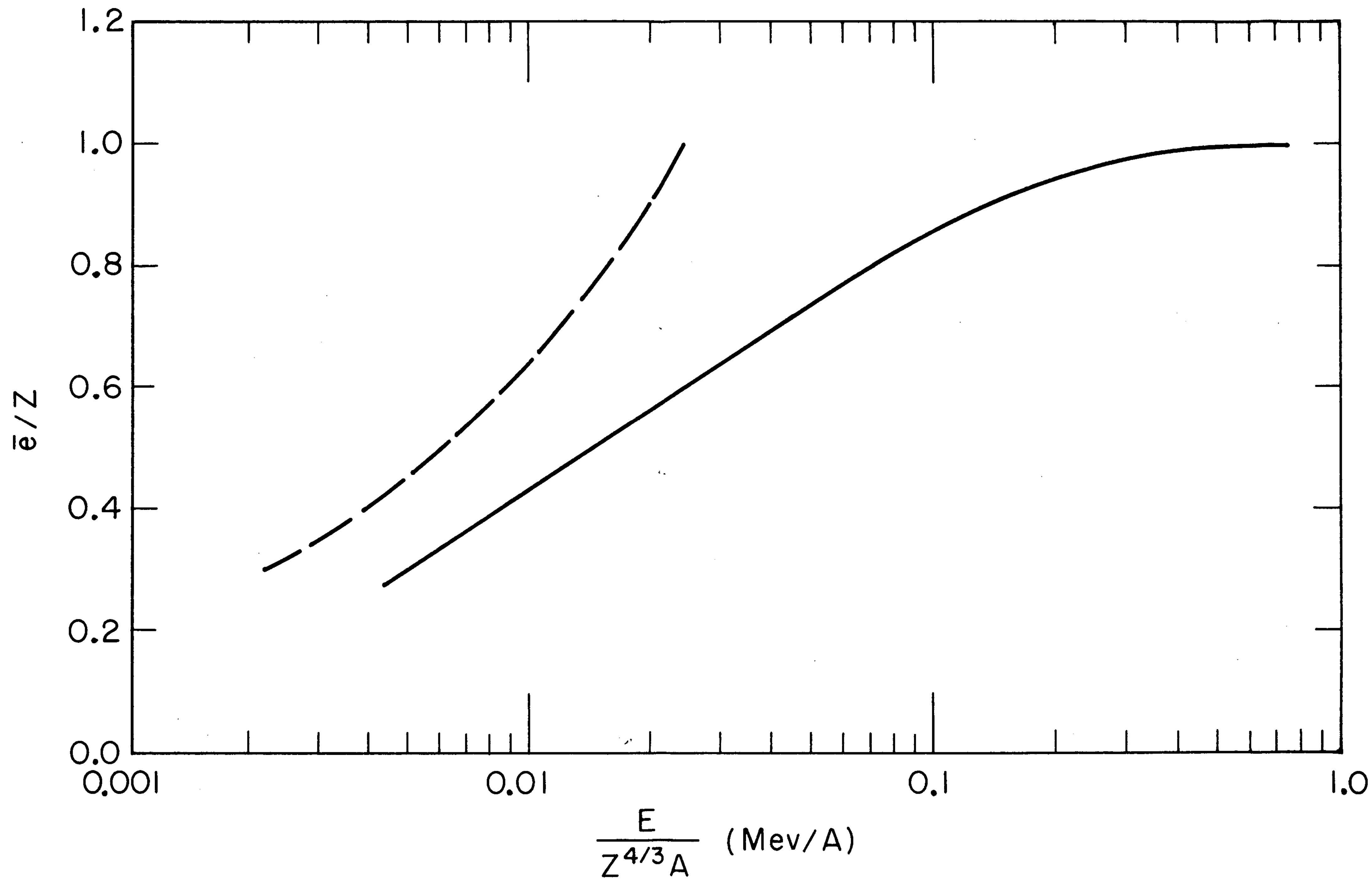


Fig 4

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