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THE PRODUCTION OF 320 MeV DEUTERONS BY HE3 STRIPPING

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Publication Date
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THE PRODUCTION OF 320 MEV DEUTERONS BY HE^3 STRIPPING

John Ise, Jr. and Robert V. Pyle, UCRL
Donald A. Hicks and Robert M. Main, CRD

August 31, 1953

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University of California, Berkeley, California

August 31, 1953

ABSTRACT

Deuterons can be accelerated in the 184-inch cyclotron to 190 Mev. To produce higher energy deuterons, doubly charged He^3 ions are accelerated to 510 Mev, and a fraction of them are stripped in an internal target, yielding deuterons with an average energy of 340 Mev. A current of 5×10^{-13} ampere is obtained in the experimental "cave" external to the cyclotron shielding. Range measurements indicate that these deuterons have an average energy of about 320 Mev.

The high cost of He^3 necessitates an efficient gas recovery system. The exhaust from the cyclotron diffusion pumps is passed through activated charcoal traps which are cooled to liquid nitrogen temperatures, and the gas which is not adsorbed (presumably helium) is returned to the cyclotron source. The loss from all causes is about 0.8 cc/hour, which represents a cost of $30 per hour of running time.

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INTRODUCTION

The purpose of this report is to describe a method of obtaining deuterons from the 184-inch cyclotron of higher energy than can be achieved from direct acceleration.

The fundamental objective of the MTA physics program is the determination of the number of neutrons produced in various targets per incident deuteron, for deuteron energies up to 500 Mev. Yield measurements have been made at several deuteron energies below and including 240 Mev, and a theory has been developed[1] from which the neutron yield may be extrapolated to higher energies. Direct measurements of the yields for energies greater than 240 Mev are nevertheless desirable, and we will describe here a technique which gives usable currents of deuterons with a distribution in energy peaked at about 320 Mev.

Deuterons can be accelerated directly in the 184-inch synchrocyclotron to an energy of about 190 Mev, whereas doubly-ionized He^3 ions have a maximum energy of 510 Mev. It was suggested by L. Alvarez that He^3 ions could be stripped to produce deuterons of about 340 Mev. The angle and energy distributions of the resultant deuterons have been calculated by Warren Heckrotte,[2] from an extension of the deuteron stripping theory of R. Serber.[3] Heckrotte predicted an energy distribution peaked at 340 Mev with a half-width at half-maximum of about 50 Mev, and an angular distribution with a half-width at half-maximum of about 4.5 degrees.

Two liters (NTP) of helium enriched to 4 percent He^3 were obtained for preliminary experiments. An equal quantity enriched to 95 percent He^3 was bought from Oak Ridge, the high enrichment being necessary to produce usable external deuteron currents.

The cyclotron can be converted to He^3 acceleration in a few minutes. As shown in Table I, the He^3 frequency range is between the frequency ranges normally used, but the r.f. system can be made to work satisfactorily by adding and removing a few condensers in the oscillator circuit.

Table I

Cyclotron Oscillator Frequency Ranges

	Start	Finish
H^1	22.9 MC	15.8 MC
He^3	15.3	12.0
H^2, He^4	11.5	9.8

The remainder of the report will be devoted to discussions of (1) the gas recovery system, (2) the extraction of the stripped deuterons, and (3) the energy distribution of the external deuteron beam.

THE GAS RECOVERY SYSTEM

Because of the high cost of the gas ($80,000 for the 95 percent He^3) it was necessary to develop a very efficient recovery system, preferably of the continuous flow type. Of the several methods of purifying the noble gases, the method of physical adsorption of impurities in an activated charcoal trap cooled to liquid nitrogen temperatures was chosen. This is preferable to the methods involving chemical separation by passage of the gas over heated metal shavings because of the greater ease and convenience.

Charcoal traps at the temperature of liquid nitrogen have been used frequently to purify helium, neon, and hydrogen, and there is a considerable body of data on the adsorption of common gases by activated charcoal,[4] but most experimenters have been concerned primarily with the removal of the contaminants, and only secondarily with the loss of a certain amount of gas in the process. In experiments involving the continuous circulation of He^3 through the cyclotron it is necessary to trap out all of the gases except helium, and remove none of the helium itself. It should be added that information on the adsorption of helium at pressures below one mm Hg is sketchy.

To determine whether the desired operation was obtainable, natural helium mixed with various amounts of air (to simulate outgassing and leaks in the cyclotron) was circulated through the recovery traps. After runs of several hours, the total volume of helium as read on a standard Bourdon gauge did not decrease perceptibly, and mass-spectroscopic analysis proved that only very slight traces of the other gases remained at the end of the run. The method, therefore, appeared feasible.

The recovery system shown in Figs. 1 and was then built. The oil-diffusion pumps of the cyclotron are backed by a 100 CFM Kinney mechanical pump, the exhaust of which is pumped through 150 feet of 1 in. copper tubing by a small Kinney pump (Model CVM 3153). Immediately in front of the latter is the purifying trap, which is a flattened steel cylinder of 1 in. by 5 in. elliptical cross section and 10 in. high. The trap is filled with activated charcoal and immersed in a five liter flask filled with liquid nitrogen. From the necessary rate of flow (about 300 cc/hr) and the average rate at which contaminating gases are picked up (measured at the exhaust of the 100 CFM Kinney pump), it has been calculated that the charcoal will remove all impurities from the circulating helium for a period of about 12 hours.

When this trap has adsorbed contaminants to its capacity, as indicated by a rising fore-pressure at the small Kinney pump, it is closed off and an identical trap which is in parallel with it is opened up to the system. A heating jacket is then placed around the first trap, which is raised to 160° C and pumped on by mechanical pump No. III (Fig. 1) until it is once more ready for use.

After leaving the trap, the helium is pumped by the small Kinney through another charcoal trap (to remove oil vapor) and into the filament stem of the cyclotron through 1/4 in. copper tubing. The rate of flow into the cyclotron is controlled by means of a needle valve.

As is shown in Fig. 1, the recovery system consists of two parts, one for the 4 percent He^3, and the other for the 95 percent He^3. The full amounts of these gases, about two liters at NTP, are never committed to the continuous flow system, but instead are contained in two brass tanks. About 5 percent of the gas in one of these tanks can be bled off into a bypass line, and it is only this smaller quantity which is continuously cycled through the cyclotron. This allows a more sensitive measure of the gas losses, and considerably lessens the amount of gas which could be lost through a leak in the cyclotron tank or pumping lines.

In the case of the 95 percent He^3, even the 100 cc of gas in the circulating system represents an investment of several thousand dollars, so several safety precautions were included in the design. All parts of the system, including the exhaust line from the small Kinney pump up to the needle valve which controls the gas flow, operate below atmospheric pressure, so that leaks which may occur are always from the atmosphere into the system and should not result in a loss of helium. However, a sudden large influx of air would be more serious, as it would almost instantly overload the purification traps. To minimize the loss from such an occurrence, a sensitrol relay is included to actuate solenoid valves which can isolate the recovery system proper. If the thermocouple pressure rises above a pre-determined point, the valves close and the gas flow is stopped.

Except for the needle valve and the two safety solenoid valves, all valves are of a high-grade commercial bellows type. Vacuum joints at points which must be broken, as at the traps, are of standard neoprene-gasketed fittings, and have given no trouble.

The one real trouble encountered has been a recurrent leak at the shaft seal of the 100 CFM Kinney pump, which was not designed to operate with vacuum on the exhaust side. To permit it to do so, the oil reservoir had to be raised eight feet to obtain sufficient pressure head to lubricate the shaft. Even after this modification, the packing gland on the shaft had to be tightened to such a degree that it rapidly burned out. A conversion kit was obtained from the manufacturer, and the packing gland seal was replaced with a type used on the smaller pumps, i.e., a rotating, oil-lubricated, graphite ring. No further trouble has been experienced since this modification was made.

There are other possible sources of helium loss, including adsorption on the interior surfaces of the cyclotron and associated vacuum lines, absorption in the oil of the diffusion pumps and mechanical oil pumps, adsorption in the charcoal traps, and loss of the ionized particles in the beam (which is completely negligible at present beam levels). In addition, when the filament is changed or probes are removed, and at the end of a run, some compromise must be reached as to the amount of time allowed to recover the helium from the cyclotron tank and vacuum lines. A period of one-half hour seems satisfactory, but some helium is undoubtedly lost.

At present, the loss from all causes is about 0.8 cc/hour, which represents a cost of about $30 per hour of running time.

THE EXTRACTION OF THE STRIPPED DEUTERONS

The 510 Mev He^3 nuclei are stripped in a one-inch beryllium target mounted on the main probe (see Fig. 2). The position is variable in radius and to some extent in azimuth (between positions 1 and 2 of Fig. 2). The stripped deuterons have radii of curvature about 4/3 as large as the He^3 and quickly leave the cyclotron. A small fraction of them pass through the deuteron tube, through a steering magnet (which also acts as an energy selector), and into the experimental "cave" outside of the shielding. The external beam is a maximum when the stripping target is at a radius of 81 in. and at azimuthal position No. 2.

The internal He^3 ion beam was measured with a current probe to be about 5×10^{-7} amperes when the 95 percent He^3 gas was used, giving an external deuteron beam of 5×10^{-13} amperes. The 4 percent enriched helium produces an external beam of about 2.5×10^{-14} amperes. Because of the difficulty in measuring currents of this order with the electrometers available, these currents are on the borderline for attenuation and range measurements. Furthermore, the measurement of internal yields (neutrons per deuteron) in extended targets requires currents of at least 2×10^{-12} amperes. The external yields can be measured with some difficulty in the $MnSO_4$ tank[5] at 5×10^{-13} amperes.[6]

In an attempt to find a method of increasing the external deuteron beam, the distribution of stripped deuterons inside of the cyclotron tank was measured with two cylindrical ion chambers mounted on the proton probe cart. These were surrounded by brass shields of sufficient thickness to stop He^3 ions and stripped protons, but still thin enough to permit the stripped deuterons to enter the chambers, and were spaced 18 in. apart in azimuth. They were also placed at slightly different radii so that one did not shield the other. The cart was moved radially and the ionization produced in the chambers was plotted as a function of radius. Figure 3 shows a typical beam profile made with a 1 in. Be target at position No. 2. From such data it was found that only the outermost part of the stripped deuteron beam could enter the deuteron tube.

On Fig. 2 are drawn lines representing the positions of maximum internal deuteron beam and the outermost of the two half-intensity curves. To obtain the necessary data, the target was moved between positions No. 1 and No. 2. On the assumption that the fringing field is independent of the cyclotron azimuth, the data have been plotted as if the target had been fixed at position No. 2 and the proton probe cart run in at different azimuths. It is found that the maximum of the deuteron beam could be swung out into line with the deuteron tube by placing the stripping target at position No. 3. However, an attempt at this did not yield higher external currents, since the beam rapidly diverges in the fringing field.

We find no evidence that higher external currents can be obtained by using thicker stripping targets, but it would appear that a considerable improvement can be made by moving the deuteron tube. Further studies are being made to determine the feasibility of this method.

ENERGY SPECTRUM OF STRIPPED DEUTERONS

The theoretical study regarding the energy spectrum of the deuterons stripped from the 510 Mev He^3 ions indicated a half-width of about 50 Mev. No experimental check is at present available on this prediction, but it is possible to calculate the energy distribution of the deuterons after emergence from the focus magnet and the deuteron tube, by means of the attenuation curves of the deuterons in uranium. The deuterons obtained from stripping of the 4 percent He^3 beam were allowed to traverse various thicknesses of uranium absorber and were then captured in the copper block of a Faraday cage, constructed to measure currents lower than 10^{-15} ampere. The beam incident upon the absorber was monitored meanwhile by means of a parallel plate ionization chamber. A full report of the construction and operation of the Faraday cage is being written and will appear in the near future.

The experimental attenuation curve is shown in Fig. 4. We have shown[7] from a study of the attenuation of monoenergetic 190 Mev deuterons that the attenuation curve can be explained quite satisfactorily, at this energy, by means of only three cross sections, all essentially independent of particle energy:

(1) attenuation of the deuterons with a total inelastic cross section σ_1 of 3.75 barns,
(2) stripping of the deuterons with a total stripping cross section σ_2 of 1.75 barns,
(3) attenuation of the stripped protons with an effective attenuation cross section σ_3 of 2.0 barns.

Consider the external deuteron beam from He^3 stripping, incident upon an attenuator of thickness t. Let the range of deuterons of energy E in this attenuator be R(E), and the energy spectrum of the deuterons (number of deuterons/cm^2/sec in an energy interval dE about E) be represented by N(E)dE. Then the number of deuterons emerging from the attenuator is

$$\int N(E) e^{-\sigma_1 t} dE$$

where the integral is extended over the energy spectrum of the incident deuterons above the minimum energy necessary to traverse the absorber.

If the coordinate x denotes distances into the attenuator parallel to the beam, measured from the front face of the attenuator, then the number of stripped protons produced in a small interval dx at a distance x is

$$\int N(E) e^{-\sigma_1 x} \sigma_2 dx \, dE.$$

Not all of these stripped protons escape from the attenuator, since (neglecting the pick-up of energy, about 7 Mev for uranium due to the different Coulomb repulsions of the incident deuteron and emergent proton after stripping[7]) the range of the stripped protons is half that of the deuteron from which it was stripped, if we assume that on the average the stripped proton has half the energy of the deuteron from which it was stripped. The total range of protons produced at a distance x inside the attenuator by deuterons of <u>initial</u> range R(E) is

$$x + \frac{R(E) - x}{2} = \frac{R(E)}{2} + \frac{x}{2} .$$

Only those protons will emerge from the attenuator of thickness t, for which

$$\frac{R}{2} + \frac{x}{2} \geqslant t, \text{ or}$$

$$x > 2t - R$$

so the total number of charged particles escaping from the attenuator is

$$\int dE\, N(E) \left\{ e^{-\sigma_1 t} + \sigma_2 \int_{x(E)}^{t} e^{-\sigma_1 x - \sigma_3 (t - x)} dx \right\}$$

$$= \int dE\, N(E) \left\{ e^{-\sigma_1 t} + \frac{\sigma_2 e^{-\sigma_3 t}}{\sigma_3 - \sigma_1} \left[e^{(\sigma_3 - \sigma_1)t} - e^{(\sigma_3 - \sigma_1)x(E)} \right] \right\} \quad (1)$$

where $x(E) = 2t - R(E)$ for $R(E) < 2t$

$= 0$ for $R(E) > 2t$

For $t < \frac{R(E)}{2}$, $x = 0$, and the factor in braces becomes

$$\left\{ e^{-\sigma_1 t}(1 - \alpha) - \alpha e^{-\sigma_3 t} \right\} \quad (2)$$

where $\alpha = \sigma_2/(\sigma_1 - \sigma_3)$.

For attenuator thicknesses $t > \frac{R(E)}{2}$, $x + 2t - R(E)$, and the factor in braces is

$$\left\{ e^{-\sigma_1 t}(1 - \alpha) + \alpha e^{(\sigma_1 - \sigma_3)R(E)}\, e^{(\sigma_3 - 2\sigma_1)t} \right\}. \quad (3)$$

It is shown in reference 7 that the coefficient α should be unity, since o_1 includes all processes which remove deuterons (and their accompanying protons) from the beam and must perforce include stripping (σ_2). Thus

$$\sigma_1 = \sigma_2 + \sigma_3 . \quad (4)$$

For a monoenergetic beam the logarithmic plot of Faraday cup current as a function of attenuator thickness t will be given by equation (2), a straight line of slope $-\sigma_3$ out to the half range, and by (3), a straight line of slope $(\sigma_3 - 2\sigma_1)$ from there on, with some rounding at the end of the range, to take into account the range straggling and the variation with energy of the various cross sections. This has been experimentally verified for 190 Mev deuterons.[7] The break between the two straight line portions does not occur exactly at the midpoint because of the net gain in energy amounting to half the Coulomb barrier or perhaps 7 Mev for uranium absorbers, when a proton is stripped from a deuteron.

The experimental attenuation curve for the He^3-stripped deuterons naturally shows no such linear behavior (Fig. 4), except for the first few millimeters of absorber, since there is expected to be a considerable energy inhomogeneity in the emergent beam. To calculate an energy spectrum which would lead to this attenuation curve, we have merely to draw attenuation curves consisting of two linear segments, for each energy interval assumed present in the beam, assign the proportions of the total beam current in the various energy bands different (unknown) weights, and using as many points on the experimental attenuation curve as we have assigned energy intervals, set up a system of algebraic equations. These equations are readily solved since all terms in matrix of coefficients below the diagonal can easily be made to vanish. That is, to find the proportion K_n of the highest energy component assumed present in the beam, we choose a thickness t_n on the experimental attenuation curve for which all the assumed lower energy components have passed the end of their range. If $I(t_n)$ is the measured Faraday cup current at this thickness, and $I_n(t_n)$ is the current corresponding to the highest energy component (obtained from the calculated linear attenuation curve for this energy) then

$$K_n I_n(t_n) = I(t_n).$$

Knowing K_n, we now choose a point on the experimental attenuation curve at which only the two highest energy components, K_n and K_{n-1}, assumed present in the beam contribute, calculate K_{n-1}, and so on.

From the definition of K_i,

$$\sum_{i=1}^{n} K_i = 1$$

This method leads to a very quick and convenient analysis of the energy spectrum and is felt to be as accurate as the experimental data warrant. It is apparent that owing to the straggling beyond the nominal range of monoenergetic particles, this method of working backward from the high energy side of the attenuation curve may introduce some cumulative error in the last low energy points to be calculated. It is not unlikely that a considerable part of the low energy tail is to be attributed to these cumulative errors.

The calculated energy spectrum is shown in Fig. 5. The significant features of the curve are:

(a) the sharp cut-off at energies above 340 Mev,
(b) the main bulk of the spectrum, centered at 320 Mev,
(c) the small low energy tail.

The shape of the spectrum is insensitive to the values of σ_2 and σ_3, but the main features of the spectrum seem to be fairly well established. A previous calculation of the energy spectrum, based on σ_1 = 3.45 barns, is also shown in Fig. 5, and reveals the same general shape, with the important differences that

(a) the new calculation leads to a considerably narrower spectrum, and
(b) the low energy tail is greatly reduced by the new value of σ_1.

A further discussion of the attenuation curve and resulting energy spectrum is given in reference 8.

A further experimental check on the shape of the energy spectrum of the stripped deuterons emerging into the cave is provided by means of the time-of-flight spectrometer[9] which consists essentially of two scintillation counters placed in the beam and separated by a known variable distance. The pulses from these crystals are fed into an ultra-fast coincident circuit, and the curve of coincidence pulse rate versus counter separation then gives the energy spectrum of the deuterons. A very preliminary run with this equipment has confirmed the narrow spectrum and the absence of the low energy tail, although the position of the peak energy is still somewhat uncertain.

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3. R. Serber, Phys. Rev. 72, 1008 (1947).
4. S. Dushman, Vacuum Technique, John Wiley and Sons, 1949.
5. W. E. Crandall and George P. Millburn, UCRL-2063.
6. MTA Quarterly Progress Report for March, April and May, 1953, UCRL-2318.
7. W. E. Crandall, et al., article to appear shortly in Phys. Rev.
8. John Ise, UCRL-2285.
9. To be published by Larry Schecter, et al.

FLOW DIAGRAM FOR GAS RECOVERY SYSTEM

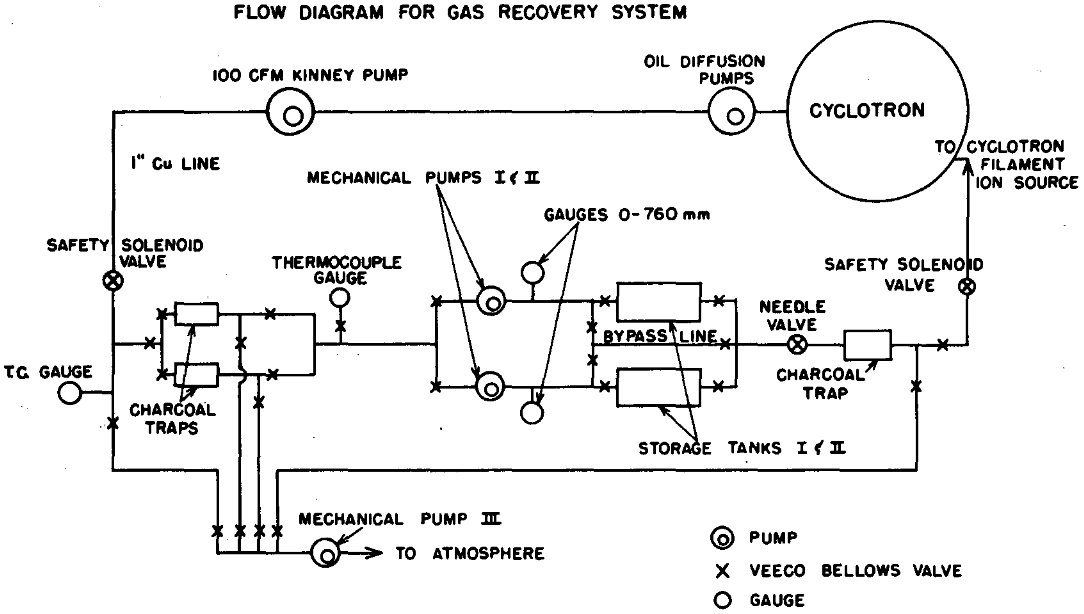

FIG. I

MU-6089

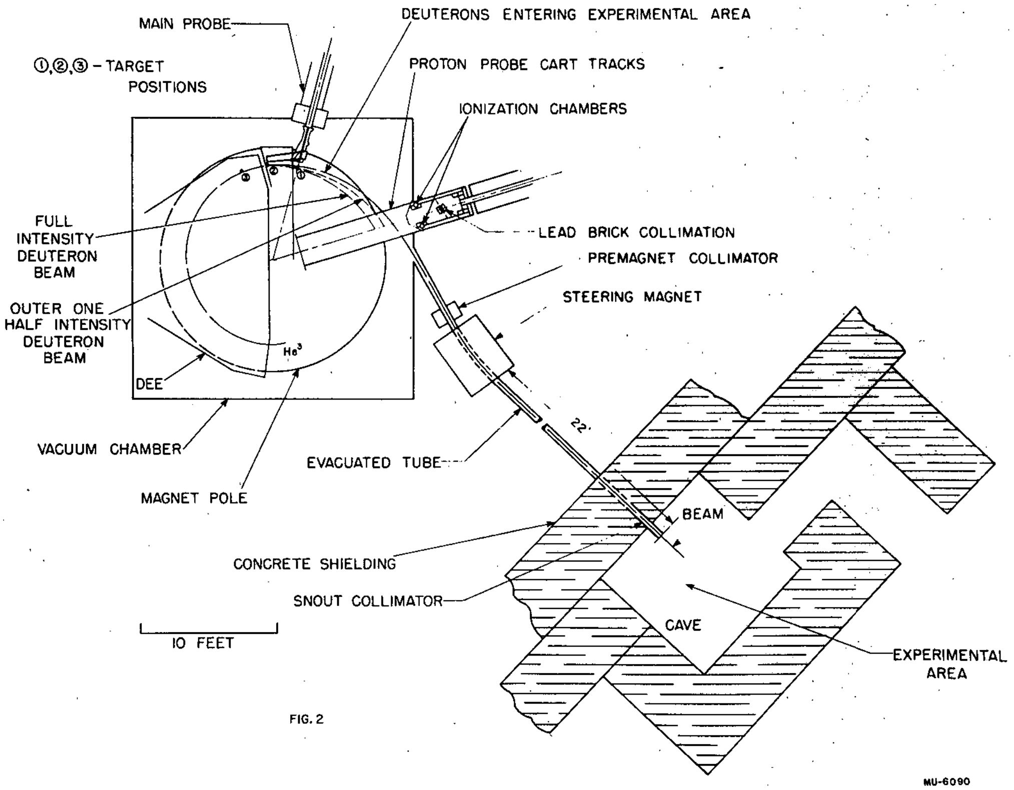
MAIN PROBE
①,②,③ - TARGET POSITIONS
DEUTERONS ENTERING EXPERIMENTAL AREA
PROTON PROBE CART TRACKS
IONIZATION CHAMBERS
LEAD BRICK COLLIMATION
PREMAGNET COLLIMATOR
STEERING MAGNET
FULL INTENSITY DEUTERON BEAM
OUTER ONE HALF INTENSITY DEUTERON BEAM
He³
DEE
VACUUM CHAMBER
MAGNET POLE
EVACUATED TUBE
22'
BEAM
CONCRETE SHIELDING
SNOUT COLLIMATOR
CAVE
EXPERIMENTAL AREA
10 FEET
MU-6090

FIG. 2

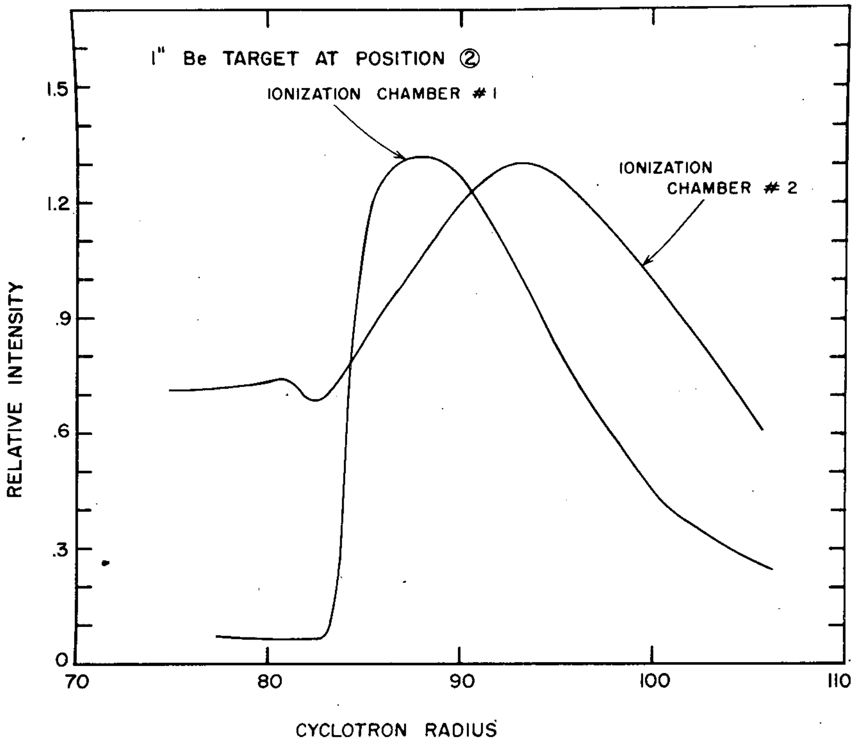
1" Be TARGET AT POSITION ②
IONIZATION CHAMBER # 1
IONIZATION CHAMBER # 2
RELATIVE INTENSITY
1.5
1.2
.9
.6
.3
0
70
80
90
100
110
CYCLOTRON RADIUS

FIG. 3

MU-6086

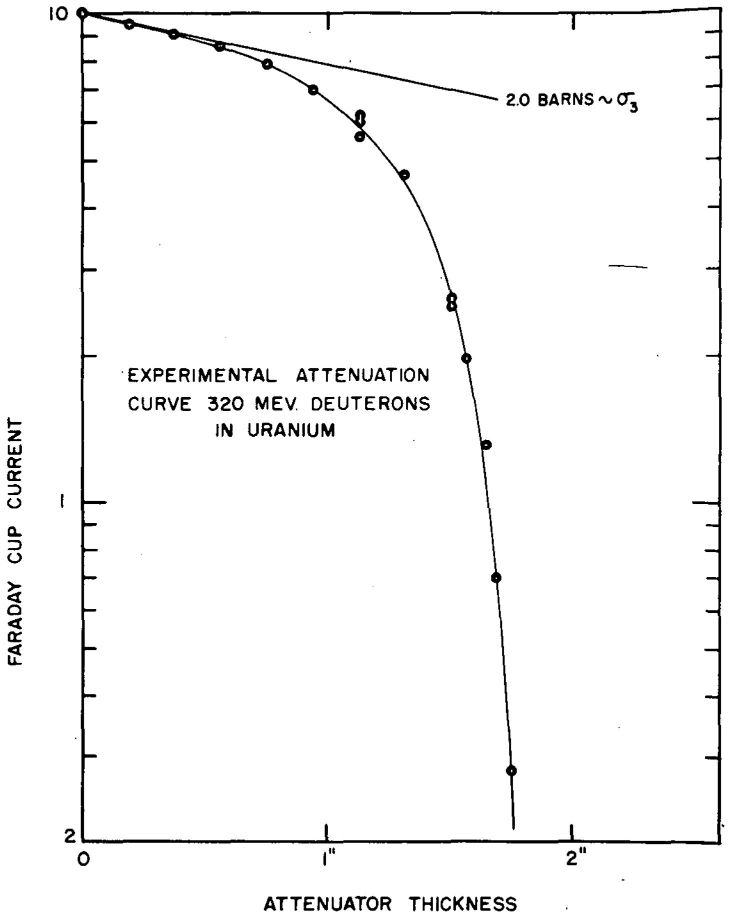
10
1
2
0
1"
2"
FARADAY CUP CURRENT
ATTENUATOR THICKNESS
2.0 BARNS ~ σ_3
EXPERIMENTAL ATTENUATION CURVE 320 MEV. DEUTERONS IN URANIUM

FIG. 4

MU-6087

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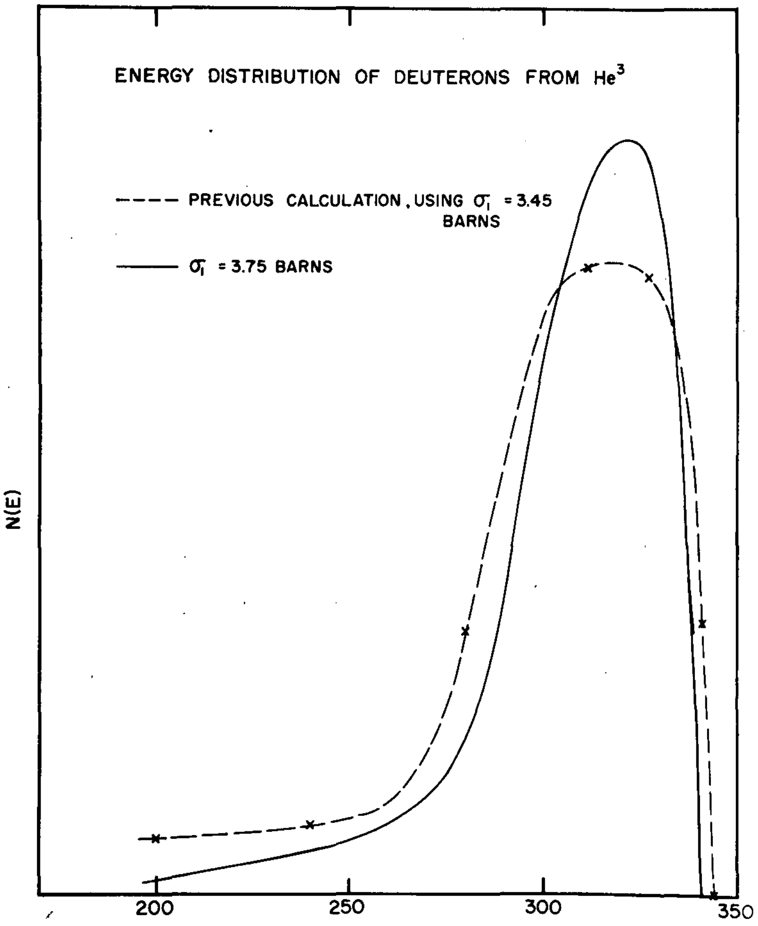

FIG. 5

MU-6088

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