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Authors
Ise, John
Pyle, Robert V.
Hicks, Donald A.
et al.

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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 0.8 cc/hour.

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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.

Deuterons can be accelerated directly in the 184-inch synchro-cyclotron 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,[1] from an extension of the deuteron stripping theory of R. Serber.[2] 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. The He^3 stripping cross section is not well known. The theory and He^3 attenuation measurements indicate that the magnitude is given by $A^{1/3} \times 10^{-26}$ cm^2.

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 GAS RECOVERY SYSTEM

Because of the high cost of the gas 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 considerable body of data on the adsorption of common gases by activated charcoal,[3] 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.

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 Fig. 1 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 a large investment, so several safety precautions were included in the design. All parts of the system, including the exhause 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.

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 at 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.

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. Fig. 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.

The experimental attenuation curve is shown in Fig. 4. We have shown[4] 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.

It has been shown[4] both experimentally and theoretically, that the logarithmic attenuation curve for monoenergetic deuterons consists of two linear portions, the first of slope $-\sigma_3$ out to half the range, and the second of slope $(\sigma_3 - 2\sigma_1)$ from there on, with some rounding near the end of the range due to range straggling and the variation with energy of the various cross sections. To explain the attenuation curve for the He^3 stripped deuterons an energy spectrum is calculated by assuming different fractions of the beam in various energy intervals, calculating the attenuation curve for each energy interval, and combining the several curves for best fit with the experimental curve.

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, and

(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 seems to be fairly well established. A previous calculation of the energy spectrum, based on $\sigma_1 = 3.45$ 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 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[5] 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 coincidence 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.

ACKNOWLEDGMENT

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REFERENCES

1. W. Heckrotte, UCRL-1868.
2. R. Serber, Phys. Rev. 72, 1008 (1947).
3. S. Dushman, Vacuum Technique, John Wiley and Sons, 1949.
4. W. E. Crandall, et al., to be submitted shortly to Phys. Rev.
5. L. Schecter, private communication.

FLOW DIAGRAM FOR GAS RECOVERY SYSTEM

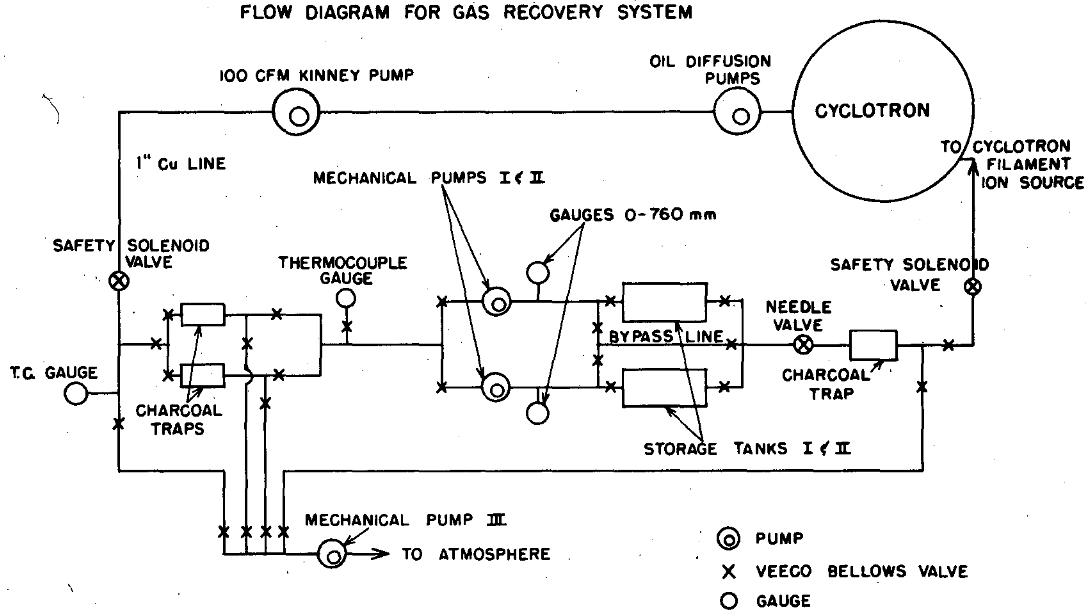

FIG. I

MU-6089

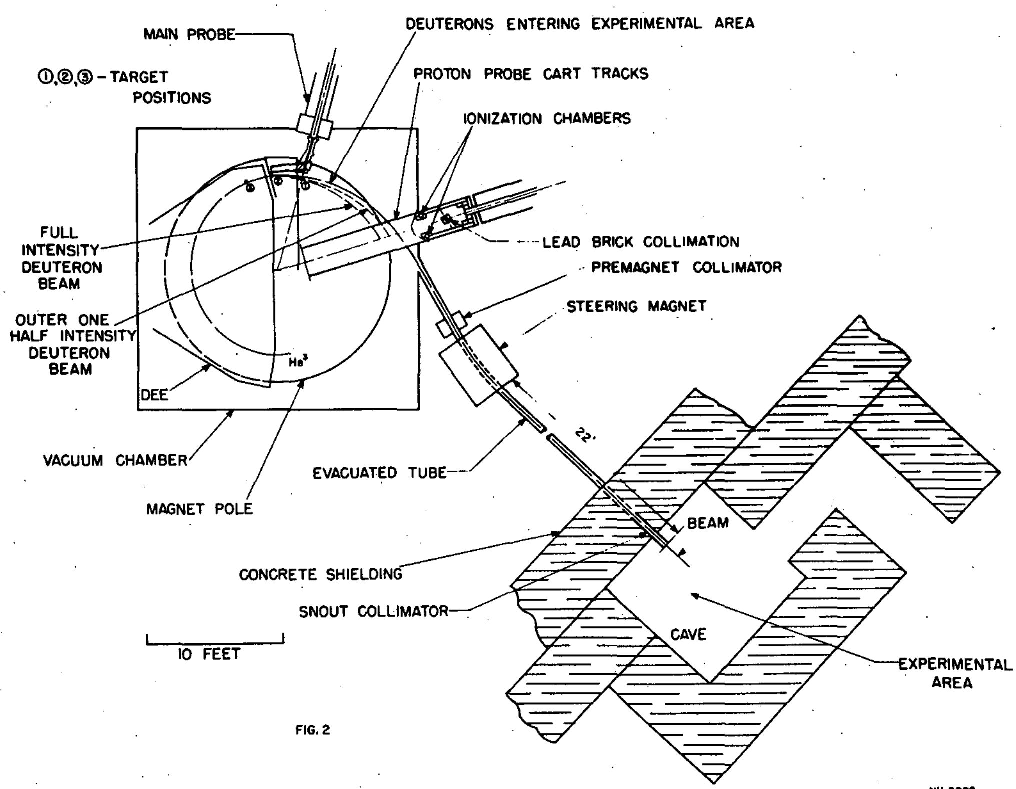
MAIN PROBE
①,②,③ - TARGET POSITIONS
DEUTERONS ENTERING EXPERIMENTAL AREA
PROTON PROBE CART TRACKS
IONIZATION CHAMBERS
FULL INTENSITY DEUTERON BEAM
OUTER ONE HALF INTENSITY DEUTERON BEAM
LEAD BRICK COLLIMATION
PREMAGNET COLLIMATOR
STEERING MAGNET
He³
DEE
VACUUM CHAMBER
MAGNET POLE
EVACUATED TUBE
22'
BEAM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

FIG. 2

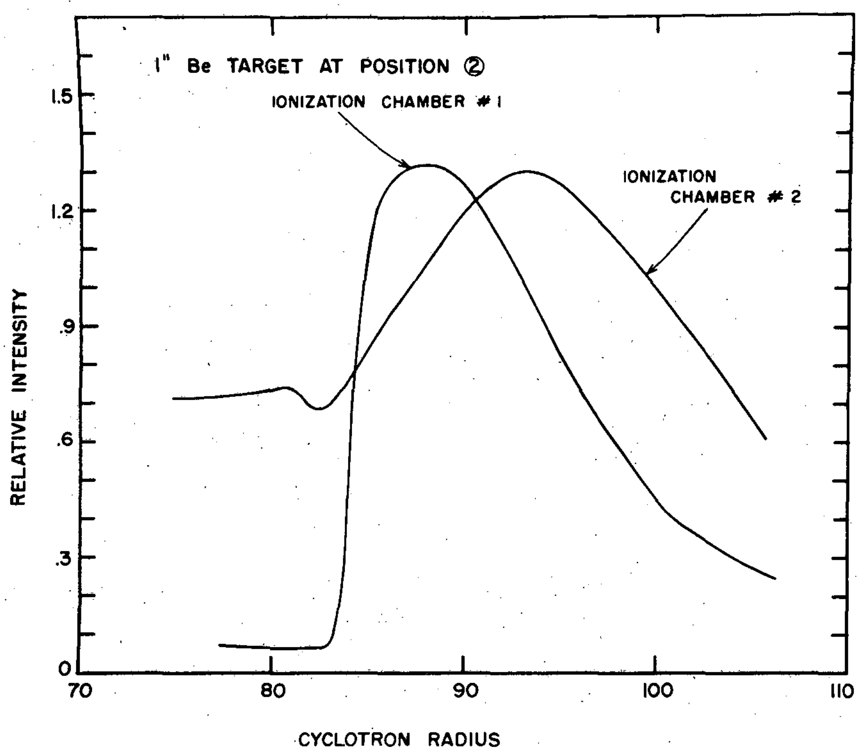
1" Be TARGET AT POSITION ②
IONIZATION CHAMBER # 1
IONIZATION CHAMBER # 2
RELATIVE INTENSITY
1.5
1.2
.9
.6
.3
0
70
80
90
100
110
CYCLOTRON RADIUS

FIG. 3

MU-6086

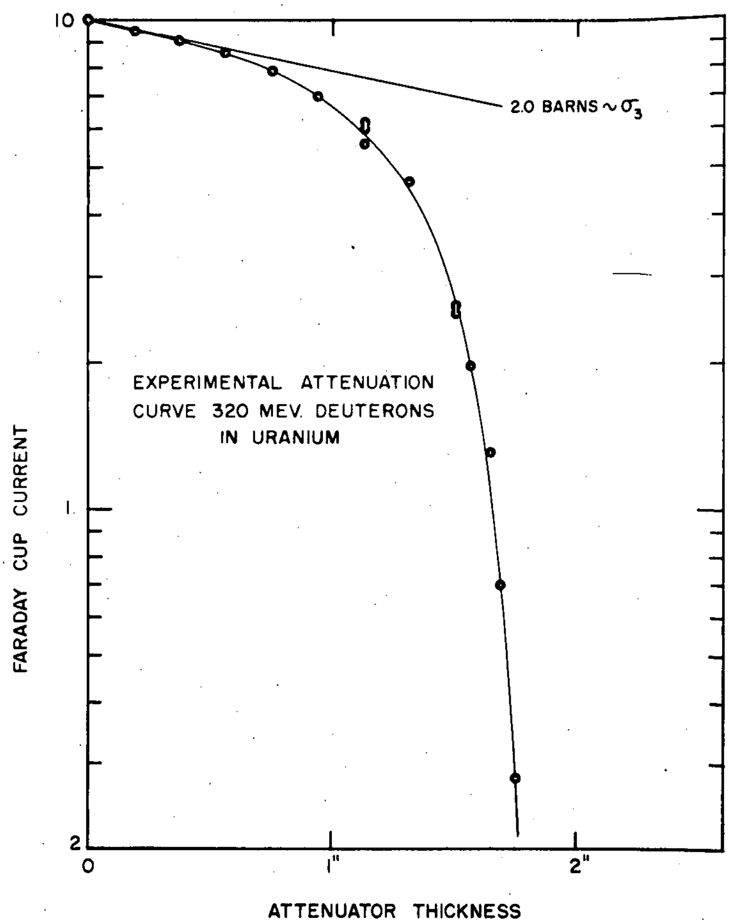
10
1.
2
0
1"
2"
2.0 BARNS ~ σ_3
EXPERIMENTAL ATTENUATION CURVE 320 MEV. DEUTERONS IN URANIUM
FARADAY CUP CURRENT
ATTENUATOR THICKNESS

FIG. 4

MU-6087

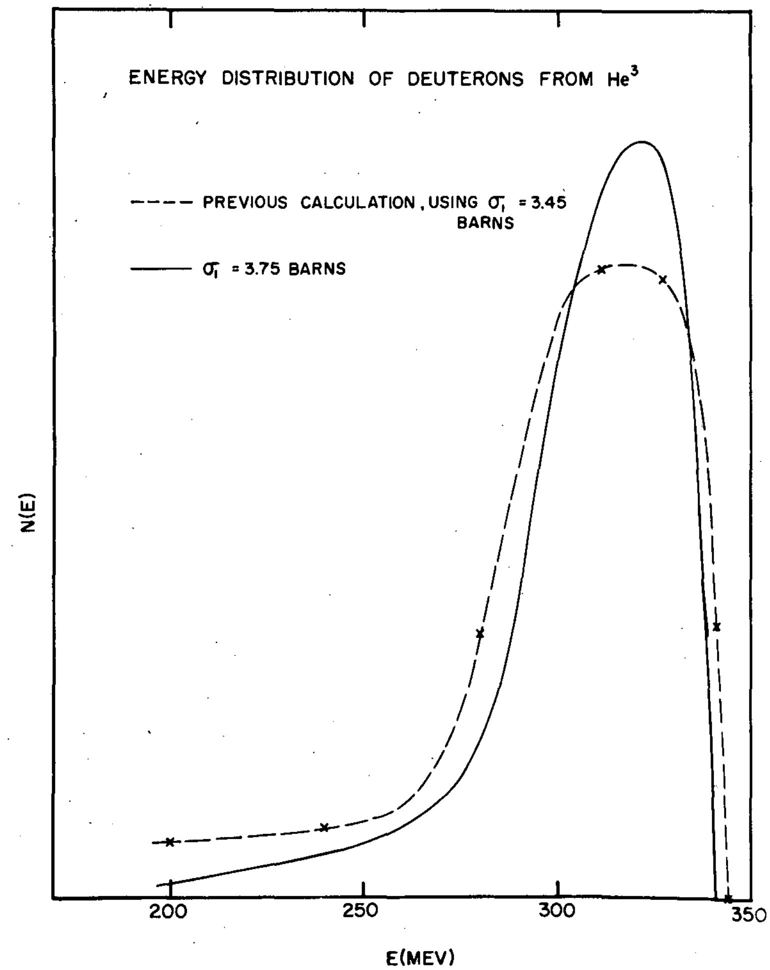
ENERGY DISTRIBUTION OF DEUTERONS FROM He³
PREVIOUS CALCULATION, USING σ₁ = 3.45 BARNS
σ₁ = 3.75 BARNS
N(E)
200
250
300
350
E(MEV)

FIG. 5

MU-6088