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MTA Cross Section Measurements

C. M. Van Atta and Harold Brown

March 2, 1951

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MTA Cross Section Measurements

C. M. Van Atta and Harold Brown

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

March 2, 1951

1. Measurement of Neutron Yields

The production of neutrons by high energy beams is based upon experiments carried out at UCRL beginning in November 1949 and still in progress. Neutrons produced in a target material by either protons or deuterons of the order of hundreds of Mev energy consist of a very high energy component of velocities approximately equal to that of the beam particles and a component of about fission neutron energy range due to nuclear evaporation. The very high energy component can produce additional neutrons in passing through matter and by this process can be multiplied by a factor of 10 or 12 by providing sufficient thickness of appropriate target material yielding neutrons again of about fission energy range.

The yield of neutrons by protons and deuterons impinging on various targets was measured using the beam from the 184-in. cyclotron. The target is placed, as shown in Fig. 1, in a tunnel which runs through a tank filled with manganese sulphate dissolved in water. Neutrons produced at the target are moderated and captured in the surrounding solution leading to the convenient 2.6 hour activity. Provisions are made for thorough mixing of the solution, a sample of which is taken for counting in a standard set-up. The solution and counting arrangement is calibrated by placing a Los Alamos standard Ra-Be source, which gives off a known number of neutrons per second, in place of the target in the tank tunnel and measuring the resulting activity produced.

The beam current is measured near the opening to the tank tunnel by means of an ionization chamber through which the beam particles pass before striking the target. The ionization chamber in turn is calibrated against a deep Faraday cup. From these measurements on incident beam particles and neutrons produced the yield of neutrons per beam particle is determined.

In testing a series of target materials with the 190 Mev deuteron beam of the 184-in. cyclotron, the yield of neutrons from at least one range thickness of each material backed up by uranium of thickness from zero up to several inches was measured. Fig. 2 shows the neutron yield (neutrons/deuteron) for several materials as a function of the uranium secondary target thickness. From this set of curves uranium used as both primary and secondary targets gives the maximum yield. This is approached fairly closely by thorium as a primary target and also by beryllium. However, as will be pointed out later on, in extrapolation to higher energy, the yield from thorium plus uranium is expected to remain essentially proportional to the pure uranium yield, whereas that from beryllium plus uranium is expected to increase with energy less rapidly than the yield from pure uranium. The comparison in yields as shown in Fig. 2 is valid only at 190 Mev for targets of greatly different atomic number.

A variety of neutron yield measurements for protons of several energies up to 350 Mev and for deuterons of several energies up to 190 Mev were made to provide insight into the theory of the process for extrapolation of the results to higher energies.

2. Extrapolation of Neutron Yield Data to Higher Energy

Direct measurement of neutron yields are limited at present to 190 Mev for deuterons and 350 Mev for protons, the maximum beam energies available from the 184-in. cyclotron. The very rapid increase in yield with energy in this energy range indicates the desirability of going to higher energy for large scale neutron production. In order to estimate the yield as a function of energy for deuterons above 190 Mev, a semi-empirical extrapolated yield curve up to 400 Mev has been obtained.

For targets of large atomic weight, two processes contribute to the total neutron yield. Deuterons may make head-on collisions with the nucleus, giving it excitation energies of the order of 100 Mev. The nucleus fissions, evaporating neutrons before and after this event, to a number up to about 20, depending on the deuteron energy and nucleus involved. Deuterons may also be stripped, with the neutron taking half the energy and proceeding in a forward direction. If an amount of uranium comparable with the range of a neutron of this energy is present, the neutron almost always undergoes an inelastic collision in which a number of neutrons roughly proportional to its energy are evaporated off by the U nucleus.

The first effect has been directly measured in differential form, by having deuterons of varying energy impinge upon a thin uranium sheet and noting the yield of neutrons, which is $N_d \sigma_{1n} (\Delta R)$. σ_{1n} is the differential cross section, R the uranium thickness, and N_d the deuteron beam current.

Since deuterons of energies above 190 Mev were not available, measurements were made using protons of higher energy. For purposes of evaporating off neutrons, a deuteron can be considered as two particles each of half the energy, and proton and neutron should behave little differently following a collision. Neglecting this difference (which probably underestimates the deuteron's effectiveness) and the binding energy of the deuteron (small compared to the kinetic energies involved), one can say that in a differential range (no ionization loss) the number of neutrons produced by a deuteron is twice the number produced by a proton of half the energy, or the number produced by a proton is half the number produced by a deuteron of twice the energy $\sigma_d(E_d) = 2\sigma_p(E_{p/2})$. Fig. 3 shows the deuteron differential cross section for uranium extrapolated to 690 Mev by this method.

In a thick target, the number of deuterons in the beam attenuates as a function of the penetration $e^{-\sigma_T x}$ where σ_T is the total cross section for nuclear events, expressed in units of in^{-1} (macroscopic cross section, which is the cross section per nucleus multiplied by the number of nuclei per unit volume). This cross section was determined roughly experimentally.

The stripping cross section σ_{1s} can be estimated from theory, but an experiment by Knox gives the value used in the calculations. The yield y_n per stripped neutron on colliding with a U nucleus is estimated from the data of Kinsey (12 at 90 Mev) and from the differential yield data on protons given herein.

The proton differential yield curve indicates a degree of saturation in y_n, but leaves the values of y_n undetermined. Furthermore, one expects that using a neutron will give 2-3 more neutrons per collision than will a proton. It is therefore not certain whether y_n is limited to 13 or so, or may rise above 20.

The protons produced in stripping processes have half the residual range of the deuterons from which they came, and will produce negligibly few neutrons. Thus a proton produced from a deuteron at 350 Mev gives about 2.3 neutrons, as compared with more than 15 from a neutron produced at the same place.

The total yield of neutrons per deuteron predicted is then

$$Y = \int_0^R e^{-\sigma_T x}\, \sigma_{1n}(E[x])\,dx + \int_0^R e^{-\sigma_T x}\, \sigma_{1s} y_n \left(\frac{E[x]}{2}\right) dx$$

where E[x] is the energy of the deuterons at a depth x in the target, and R is the range.

By plotting a theoretical curve we hope at least to be able to find out how to extrapolate the observed data.

Directly taken data includes σ_{1n} and σ_T. σ_{1s} and y_n must be estimated. Using σ_{1n} and σ_T gives a value for the integrated differential cross section which is too low compared with the experimental gross-yield, even after adding on a stripping contribution with reasonable values of y_n and σ_{1s} (7 Mev/neutron up to 100 Mev, and 1 barn, respectively). However, the slope of the log-log plot agrees, and by multiplying the calculated yield by 1.2 at all energies, the gross yield curve is adequately fitted in the measured region. The correction could, for example, be due to some geometrical difference between the differential and gross yield measurements.

It is possible to make a rough quantitative check on the division of neutron production by 190 Mev deuterons into direct production and that by stripping. Fig. 4 shows the yield as a function of total (primary + secondary) target. A rough division can be made by saying

$$N = N_{direct}(x) + N_{stripping}(1 - e^{-x/x_1})$$

with x_1 the mean free path for multiplication of stripped neutrons $N_{direct}(x)$ = constant for $x > R$. These assumptions agree well with the shape of the curve, and yield $x_1 = 0.75$ in. and $N_d \cong 2.2$, $N_s \cong 1.0$ as compared with computed values of 2.3 and 0.9 respectively. x_1 corresponds to a 10 barn cross section, which seems high until one realizes that any collision with a U nucleus by a stripped neutron, though it may not produce multiplication, makes the expected further penetration of that neutron in the forward direction exceedingly small (by absorbing its forward momentum).

The slope of the Y vs. E curve is such that $Y \propto E_d^{2.5}$, or $Y \propto RE_d^{0.8}$ (R the range). How the curve behaves above measured E_d's depends upon the assumption one makes about the number of neutrons which are evaporated when a fast stripped neutron hits a U nucleus. If this goes to a limit at about 100 Mev, the gross-yield will level off quite sharply at $E_d \sim 200$ Mev (Fig. 4, curve 1a), the slope falling to about 1.7 at $E_d \sim 350$ (so $Y \propto R$).

However, if the number of neutrons evaporable in a single event can rise to 25 for a 200 Mev neutron (number roughly proportional to incident neutron energy) the yield curve does not flatten out so soon or so much, behaving something like $Y \propto E^{2.2}$ at E_d = 350 Mev (curve 1b).

The differential yield curve for protons indicates a behavior for production by stripped neutrons intermediate between these two assumptions.

Using the above slopes and the experimental gross-yield data, one gets 9.1 and 10.5 neutrons at 350 Mev. The single point rechecked, however, (for 190 Mev deuterons) in new measurements, has been raised from 2.8 to 3.2 neutrons/deuteron. This results from using a thicker uranium multiplier and a much larger tank for the manganese sulphate solution. Applying a similar ratio at 350 Mev gives 10.4 and 12.0 respectively. In view of these numbers, it seems almost certain that the yield at 350 will lie between 9 and 12, with 11 perhaps the best estimate. For 250 Mev the corresponding limits are 5.2 and 6.4 with 5.5 neutrons per deuteron as the best estimate.

Measurements shown in Fig. 2 indicate that the yield from a thorium primary target (one range thick) backed up with a uranium secondary is about 85 percent that for uranium. This ratio is expected to be roughly independent of the deuteron energy. For light metal primary targets backed up with a uranium secondary, however, the yield is expected to increase only slightly faster than linearly with the deuteron energy. Thus, although the yield of beryllium plus uranium is about 80 percent of that of pure uranium at 190 Mev, the corresponding relative yields are expected to be only about 65 percent at 250 Mev and 50 percent at 350 Mev.

The yield measurements made specifically for the purpose of extrapolating results to higher energies seem to have successfully demonstrated the dependence of yield on energy as well as can be expected and therefore repetition of these measurements is not contemplated. However, detailed measurements of yields for different target arrangements and materials for 190 Mev deuterons is being continued to provide the best possible relative yield data as a basis for target design.

3. Energy Distribution of Neutrons

The energy distribution of neutrons created by the deuterons in the primary target is believed to consist of a high energy component (mostly due to stripping) and a roughly Maxwellian distribution of neutrons evaporated from highly excited target nuclei or fission fragments. The evidence for this comes from

a. Experiments by E. M. McMillan, et al., on stripping. The energy of the stripped neutrons was found to be half that of the deuterons producing them. The stripped neutrons were found to be half contained within 9 degrees of the forward direction.

b. Experiments by B. B. Kinsey at UCRL measuring in photographic plates the energy distribution of neutrons produced in various targets by 90 Mev neutrons. The mean energy appears to be slightly higher than that for thermal fission neutrons, but depends strongly upon target thickness. Although these measurements were performed with 90 Mev neutrons, they give some indication of what is to be expected for the higher energy deuterons to be used by MTA.

c. Experiments with 330 Mev protons by Duane Sewell, et al., at UCRL indicate that very high energy nucleons may produce a high energy neutron tail by direct collision with nucleons in the target nuclei.

The distribution in energy to be expected from a very large and very thick target is dependent on the inelastic scattering properties of the target. For a sufficiently thick uranium secondary target the very high energy stripped neutrons will be essentially all absorbed and converted to a Maxwellian evaporation spectrum. At the same time this distribution will be warped by the absorption and inelastic scattering properties of uranium and will probably approach the so-called equilibrium distribution which, however, is not too well known.

Among the experiments planned for the near future at UCRL is a sort of Snell experiment to establish the neutron energy distribution. Experiments are also contemplated for determining the energy and angular distribution of the neutrons from thin targets bombarded by 190 Mev deuterons.

4. Spallation and Fission Product Distribution

Information relative to the distribution of spallation and fission products in uranium has been obtained for 350 Mev protons by O'Connor and Seaborg (Phys. Rev. 74, 1189 (1948)) and for 400 Mev alpha particles by Folger, Stevenson and Seaborg (unpublished). The yield curve (relative to Ba^{140}) for the former case is given in Fig. 5. The peak of the fission yield curve is at the center corresponding to symmetric fission. The spallation yield is represented by the rise in the yield curve at high A. The yield seems to be about 10 percent spallation and 90 percent fission, with a total cross section of about 2.5 barns.

A fission product distribution approximately like that shown in Fig. 5 is expected for the MTA primary target. Experiments are now in progress to determine fission product yield curves of the type for the complex of charged and neutral particles to be found at various depths in the target. It is also planned to determine the amounts of various activities to be found as a function of the time after bombardment. This information is needed in the design of shielding and in the specification of cooling for the target after shut down.

This work was performed under the auspices of the Atomic Energy Commission.

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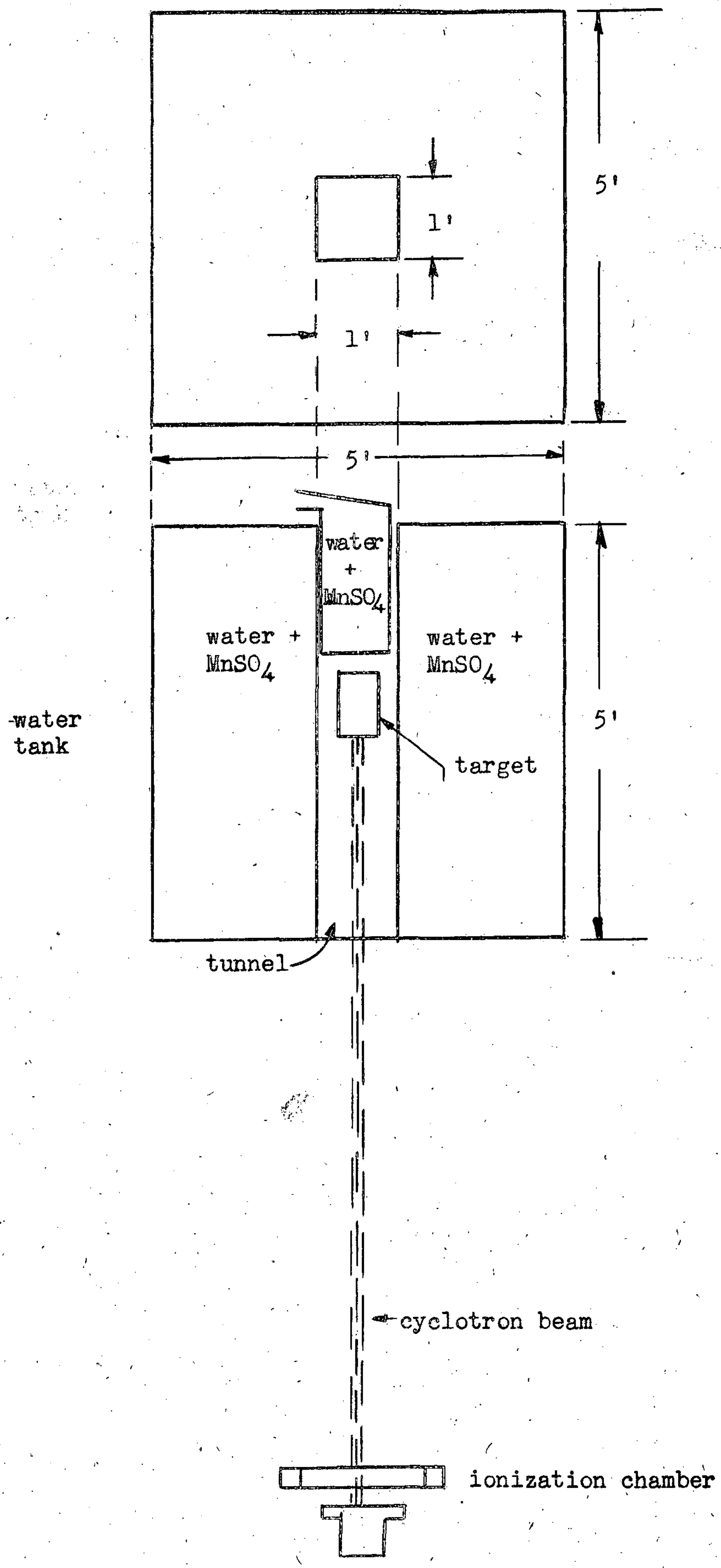
5'
1'
1'
5'
water
+
MnSO4
water +
MnSO4
water +
MnSO4
water
tank
5'
target
tunnel
cyclotron beam
ionization chamber

Fig. 1

GROSS YIELD OF NEUTRONS FOR VARYING THICKNESS OF URANIUM MULTIPLIER

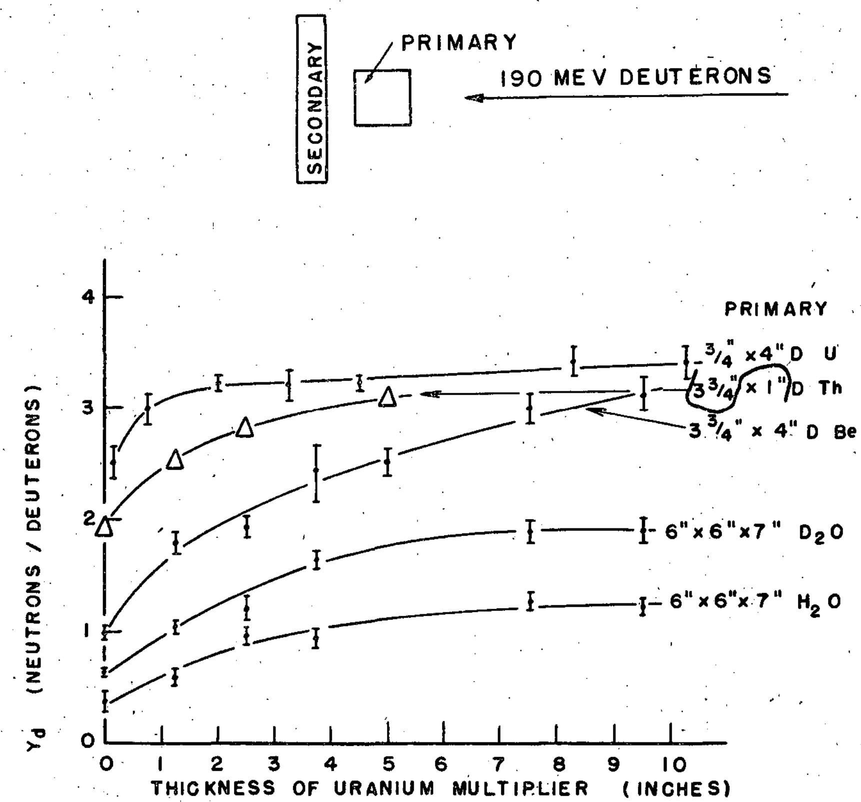

FIG. 2

MU 1465

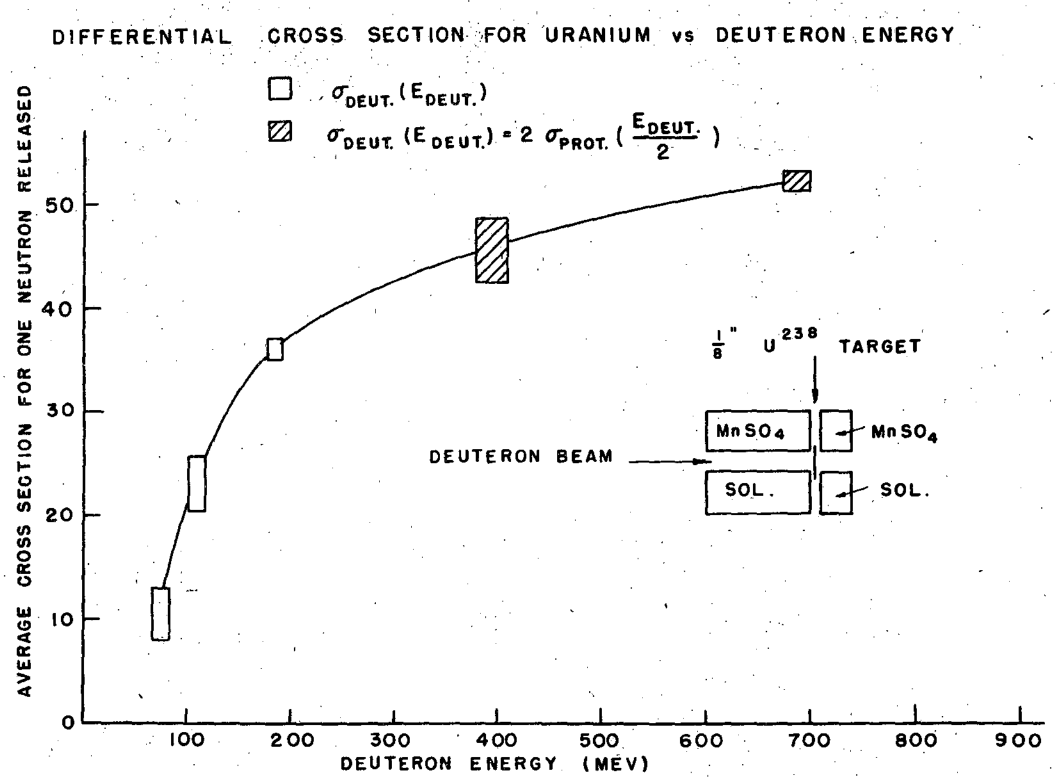
DIFFERENTIAL CROSS SECTION FOR URANIUM vs DEUTERON ENERGY
σDEUT. (EDEUT.)
σDEUT. (EDEUT.) = 2 σPROT. (EDEUT./2)
AVERAGE CROSS SECTION FOR ONE NEUTRON RELEASED
0
10
20
30
40
50
100
200
300
400
500
600
700
800
900
DEUTERON ENERGY (MEV)
1/8" U238 TARGET
MnSO4
MnSO4
DEUTERON BEAM
SOL.
SOL.
MU 1065

FIG. 3

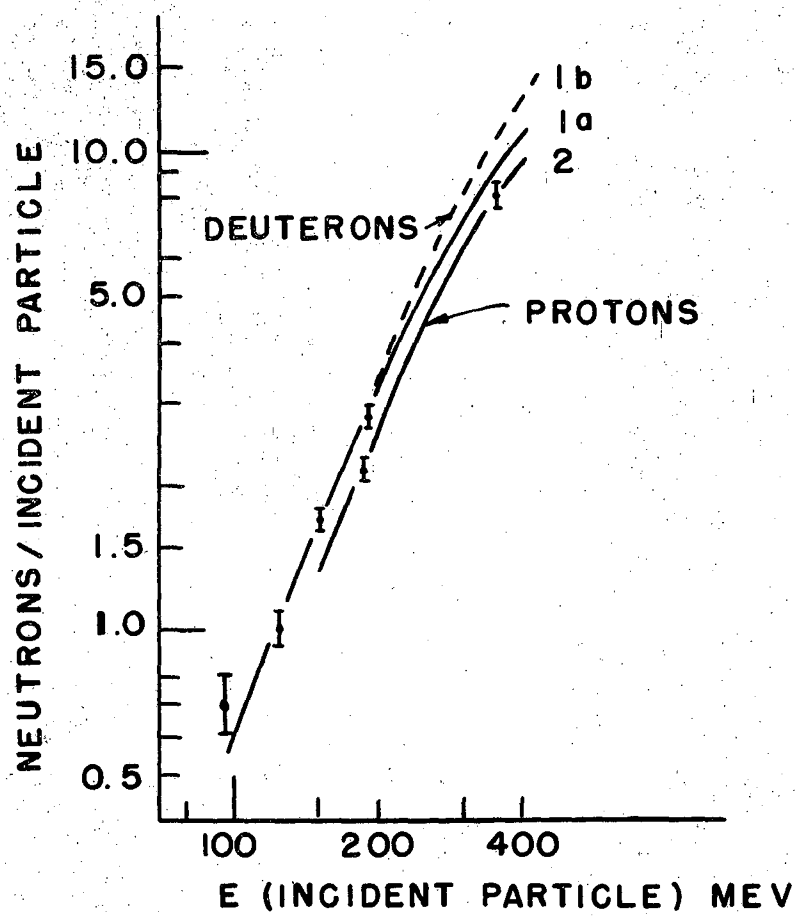
15.0
10.0
5.0
1.5
1.0
0.5
NEUTRONS/INCIDENT PARTICLE
1b
1a
2
DEUTERONS
PROTONS
100
200
400
E (INCIDENT PARTICLE) MEV

FIG. 4

MU 1066

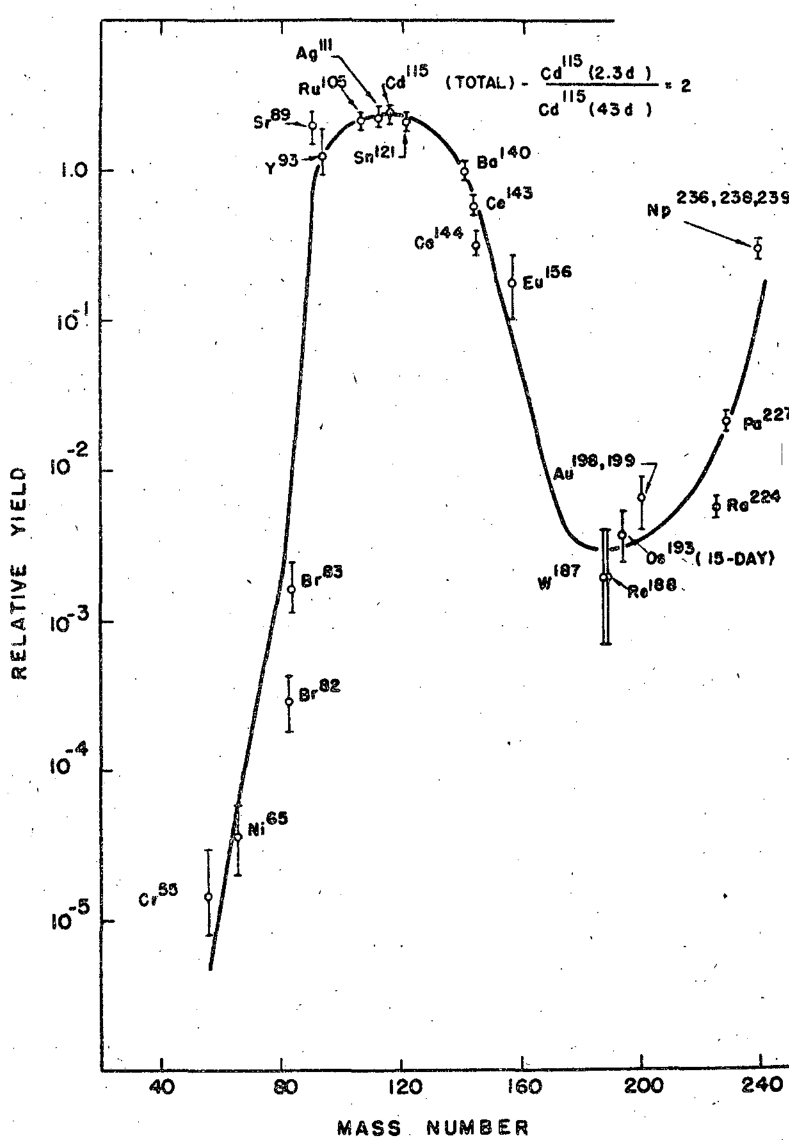

FIG. 5

1464

Relative yield curve for products from
350 Mev helium ion bombardment of uranium.