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Neutrons and Gamma-Radiation from Deuteron Bombardment of Be

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Neutron and gamma-ray intensities from thin targets of Be bombarded by deuterons were measured as a function of deuteron energy from 0.2 to 1.8 Mev. Most of the neutron data were obtained in the forward direction with respect to the deuteron beam. Neutron and gamma-ray intensities show exponential increase with energy below 800 kev; a broad resonance in the region 1.0 to 1.1 Mev is indicated by the shape of the curve at energies above 800 kev. Search revealed no sharp resonances. Evidence is shown for a previously unknown neutron group of Q equal to -0.7 Mev. Neutron intensities were measured as a function of angle with the deuteron beam for a number of bombarding energies from 0.8 to 1.7 Mev.

INTRODUCTION

THE reaction

$$Be^9+H^2\rightarrow{}^*B^{11}\rightarrow B^{10}+n^1+4.3\text{ Mev}$$

has been used extensively as an intense source of fast neutrons since its discovery and early investigation.[1] Amaldi, Hafstad, and Tuve[2] made precise measurements of thick target yields for bombarding energies up to 1 Mev, but the thin target excitation curve has not been known. It was the purpose of this investigation to obtain the thin target yield function for neutrons and gamma-radiation up to the limiting energy of the Rice Institute statitron (about 2 Mev). Moreover, since resonances have been observed in the deuteron bombardment of other elements, e.g., lithium and carbon,[3] it was thought that the neutron and gamma-ray yield of the $Be^9(d,n)B^{10}$ reaction might also show narrow resonances which would yield valuable information on the excited states of B^{11}. Surveys were made of the angular distribution of the neutrons for several bombarding energies, since it has been shown that particle yields depend to a marked degree on the angle of observation.

Bonner and Brubaker[4] showed that at a bombarding energy of 0.9 Mev there are four groups of neutrons with Q values of 4.25, 3.7, 2.1, and 0.8 Mev. From recent investigations with a gamma-ray spectrometer,[5, 6] gamma-ray energies of 411, 475, 718, 1024, 1435, 2170, 2924, and 3425 kev are reported. The 411 and 718-kev line have been attributed[5] to B^{10}. The energy values of other lines, e.g., 2170 and 3425, agree with differences in energy of the neutron groups. Some lines must, however, be attributed to the competing reactions involving charged particles: the 475-kev line is assigned[5] to the $Be^9(d,\alpha)Li^7$ reaction, where two groups of alphas with this energy difference are known,[7] and two groups of protons[8] from the reaction $Be^9(d,p)Be^{10}$ indicate an excited level at 3.4 Mev in Be^{10} which could be the origin of one or more lines.

ACCELERATING APPARATUS

The Rice Institute statitron was used to obtain homogeneous beams of deuterons of energies from 200 kev to 1900 kev, with the potential stabilizer previously described[9] maintaining constant bombarding energies during observations. The atomic beam was deflected through 90° by a magnetic analyzer, which was used to measure the energy of the beam. Following the same hysteresis cycle enables energies to be reproduced within 2 kev, and the absolute energies are known to better than 5 kev, using gamma-ray resonances in Li^7+p, $F^{19}+p$, and $C^{12}+d$, for calibration. The slit system allows a resolution where needed of 1 kev to 1 Mev, so that narrow resonances could easily have been detected. Bombarding currents were measured by a current integrator[10] which was calibrated periodically.

TARGETS

Beryllium targets from 10 to 100 kev thick were prepared by evaporation of beryllium in a high vacuum on to clean polished disks of silver, using helical filaments of tungsten or of tantalum to heat

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[1] H. R. Crane, C. C. Lauritsen, and A. Soltan, Phys. Rev. **44**, 692 (1933) and **45**, 507 (1934); M. S. Livingston, M. C. Henderson, and E. O. Lawrence, Phys. Rev. **44**, 782 (1933); E. O. Lawrence and D. Cooksey, Phys. Rev. **50**, 1131 (1936).

[2] E. Amaldi, L. R. Hafstad, and M. A. Tuve, Phys. Rev. **51**, 896 (1937).

[3] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947); Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).

[4] T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).

[5] Lauritsen, Fowler, Lauritsen, and Rasmussen, Phys. Rev. **73**, 636 (1948).

[6] T. Lauritsen, C. B. Dougherty, and V. K. Rasmussen, Phys. Rev. **74**, 1566A (1948).

[7] E. R. Graves, Phys. Rev. **57**, 855 (1940).

[8] C. M. G. Lattes, P. H. Fowler, and P. Cuer, Proc. Phys. Soc. London **59**, 883 (1947).

[9] Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946).

[10] B. E. Watt, Rev. Sci. Inst. **17**, 334 (1946).

the beryllium. While both metals have a limited solubility in beryllium, the purity of the targets was maintained by the following precautions in the evaporation: the target was uncovered only after the beryllium had formed small molten droplets and was evaporating; the filament temperature near the droplets as determined by a pyrometer was not allowed to rise more than 100°C above the melting point of beryllium (1350°C); the procedure was stopped as soon as the evaporation of the residual droplet became slow; vacuum of 5×10^{-5} mm Hg or better was obtained preceding evaporation, since oxidation of the beryllium prevents evaporation at low temperatures. The chemical analysis of the beryllium which was used indicated traces of impurities only: 0.1 percent Fe, 0.1 percent Al, and 0.1 percent Si. These would not be expected to produce a detectable yield, and they were probably reduced in quantity by the evaporation procedure. Target thicknesses were determined by weighing on a microbalance, and checked by comparing yields with that of a thick target machined from a beryllium chunk.

Targets were discarded as soon as definite discoloration indicated an appreciable deposit of carbon from the vacuum system; many standardized measurements of the positron annihilation radiation of N^{13} after target bombardment showed this to be adequate precaution. The N^{13} positrons were counted directly on one discarded target characterized by more than average carbon deposit. Direct comparison with carbon targets of known thickness (used in determining the cross section for the $C^{12}(d,n)N^{13}$ reaction[11]) allowed the carbon contamination activity on this target to be determined as 2.0 percent of the target activity for gamma-rays and 2.7 percent for neutrons at 880 kev. Data taken with this target (the bulk of the data at 0° above 800 kev) was then corrected for the carbon activity. Unless otherwise specified, all data were taken with targets on which 2 percent for gamma-rays and 3 percent for neutrons is believed to be the upper limit for target contamination.

GAMMA-RAY YIELD

Counter Arrangement

The gamma-rays were detected with self-quenching Geiger-Mueller counters and an Instrument Development Laboratories scale of 64 unit with amplifier and regulated power supply. The gamma-ray counter was a small commercial counter obtained from Herbach and Rademan. It had a 0.005-in. thick copper cylinder 1.0 cm D and 3.0 cm long enclosed in a glass envelope about 0.050″ thick. It was mounted in a 0.031-in. wall brass tube. It was used primarily because of its small effective area, which allowed positioning close to the target without excessive counting rates. In the preliminary measurements and search for resonances, and for all data below 800 kev, the gamma-ray counter was an Eck and Krebs counter with a silvered glass wall surrounded by a $\frac{1}{16}$-in. brass tube. Using the 2.6-Mev gamma-ray of ThC″ as a gamma-ray source, the efficiency of the two counters was found to be essentially the same, the small Herbach and Rademan counter being 93 percent as efficient per unit effective area as the Eck and Krebs counter, although the latter had somewhat simpler geometry since essentially all secondary electrons came from the thick wall brass tube. We therefore feel justified in assuming efficiencies for both counters equal to those reported for gamma-ray counters by several workers.[12]

The positioning of the counter with respect to the target and defining slits of the magnetic analyzer is shown in Fig. 1. The extension of the vacuum tube beyond the slit is long enough so that background radiation from the slits and walls of the magnet box is cut down appreciably relative to radiation from the target. The final gamma-ray excitation curves above 800 kev were taken in the position shown, with the axis of the gamma-ray counter 6 cm from the center of the target.

The distance from the counter axis to the slits was somewhat over 45 cm so that, from solid angle, the background from the slits and nearest part of the magnet chamber is down by a factor greater than 50 with respect to target radiation. Lead slabs milled to fit closely about the vacuum tube, and placed as shown in the figure, provided at least 5-cm path length in lead for background radiation from any part of the magnet assembly. This is enough to cut down the 3-Mev gamma-radiation from the bombardment of carbon contamination by an additional factor of 10. For data above 800 kev a cylindrical lead shield was placed about the counter. It was 1.4 cm thick (6.0-cm O.D. and 3.2-cm I.D.) and had a milled slot so that there was no lead between the target and sensitive volume of the counter.

The measured background was never more than $\frac{1}{2}$ percent for any of the targets which were used in obtaining data for the excitation curve. This background was determined by causing the beam to fall on the low energy side of the slit instead of passing through to the target. This was believed to give at least as much background radiation as was present during target bombardment.

Counting rates were kept well under 500 per second, where the counting loss was determined as less than 1 percent for the Herbach and Rademan

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[11] Bonner, Evans, Harris, and Phillips, to be published.

[12] Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta **19**, 77 (1946); F. Norling, Arkiv f. Matematik, Astronome o. Fys. **27A**, N:04 (1941).

counter. Generally more than 2000 counts were taken for a point; in addition, each point was repeated at least once for a single run, and a number of runs were made over the region investigated. The efficiencies of the counters were checked during long runs with a 1-mg radium source.

Results

The gamma-ray excitation curve is plotted in Fig. 2. The energies are bombarding energies rather than mean energies in the target; the bulk of the plotted data was taken with a 37-kev target, with the points separated by about $\frac{3}{4}$ target thickness. The gamma-ray curve shows no sharp resonances, although the portion above 800 kev was covered in preliminary surveys with targets 10 to 20 kev thick using a slit width corresponding to 3 kev at 1 Mev. Since both counters are relatively insensitive to low energy radiation, a weak sharp resonance involving only low energy gamma-rays might not be apparent in our data.

From the low energies up to about 800 kev the yield rises as if determined by the penetrability of the potential barrier. A broad resonance located at 1.0 to 1.1 Mev, with a width of 200 kev or more, appears to be the best explanation for the shape of the curve between 800 and 1400 kev. In accord with this interpretation, good fits by barrier penetration function[13] for the deuteron can be obtained below 800 kev using reasonable angular momentum values, but not in the immediate neighborhood of 1 Mev and above.

To estimate the magnitude of the cross section, the counter efficiency was deduced from the efficiency-energy curve for a brass counter given by Bradt, Gugelot, Huber, Medicus, Preiswerk, and Scherrer.[12] Our Eck and Krebs counter (thin-wall glass counter in a brass tube 1.6 mm thick) was assumed to have an efficiency ranging from 1.8 percent at 3425 kev to 0.17 percent at 411 kev. Assuming equal intensities for all the lines, since intensity estimates are not available, the average efficiency of the counter is calculated to be 0.86 percent. From this value and our geometry the total gamma-ray cross section is calculated to be 0.43 barn at 880 kev. This agrees fairly well with the value reported by Swann, Scott, Hudspeth, and Mandeville[14] at 600 kev.

The fact that the counter was responding primarily to the higher energy quanta was corroborated by the insertion of a 1.3-cm Pb absorber, which cut down the gamma-ray intensity by the same factor (1.8 under conditions of rather poor geometry) as the 3-Mev gamma-radiation from a carbon target at 880-kev bombarding energy. Moreover, insertion of this absorber in a run from 800 to 1700 kev did not change the shape of the yield curve.

NEUTRON YIELD

Counting Technique

The neutrons were detected with proportional counters using an Atomic Instrument Company linear amplifier, discriminator, and scaler and a standard regulated high voltage supply. Two types of gas-recoil counters were used, one containing hydrogen and the other argon. The argon counter had a low efficiency but was believed to have approximately the same sensitivity for the high Q neutrons as for those of low Q. It was a cylindrical Eck and Krebs beta-ray type counter with a thin silvered glass envelope shielded with a $\frac{1}{16}$-in. brass tube. Its effective volume was 1.8 cm in diameter and 6.0 cm long, and it was filled to one atmosphere of commercial argon. The hydrogen counter consisted of a brass cylinder 4.5-cm long and 4.5-cm I.D., filled with one atmosphere of hydrogen containing 2 percent methane.

As a result of the low efficiency of the argon counter, the problem of getting statistically satisfactory data over the entire energy region was greatest for this counter. In individual runs, readings were repeated at least once for each point, with a minimum of 1280 neutron counts taken per point, i.e., at a given bombarding voltage. A run consisted of a single coverage of an energy interval with points spaced about $\frac{3}{4}$ target thickness, plus repeats on check points throughout the interval. Critical portions of the curve were covered in single runs to minimize effects of joining data taken on successive days. The entire yield curve was covered at least twice. The same precautions were taken with the hydrogen counter except that, due to its higher efficiency, the entire curve could be covered in one or two runs and generally 2000 or more neutron counts per point were taken.

In the case of the argon counter it was considered unnecessary to correct the data for the neutron yield of thin carbon contamination films deposited on the target since, as discussed in the following section, biasing makes the counter sensitivity small for the carbon neutrons as a consequence of their lower energy ($Q=-0.3$ as compared to the lowest value for beryllium of $+0.8$). For the hydrogen counter data, however, correction was made for carbon deposit as discussed in the section on targets, although the correction even in this case was small.

The positioning of the neutron counters for the excitation curves in the forward direction is shown in Fig. 1. Eleven centimeters, or more, of paraffin along the vacuum tube shielded the counters from carbon neutrons originating in the magnet chamber and at the slits, except those which proceeded

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[13] H. A. Bethe, Rev. Mod. Phys. 9, 178 (1937).

[14] Swann, Scott, Hudspeth, and Mandeville, Phys. Rev. 73, 648A (1948).

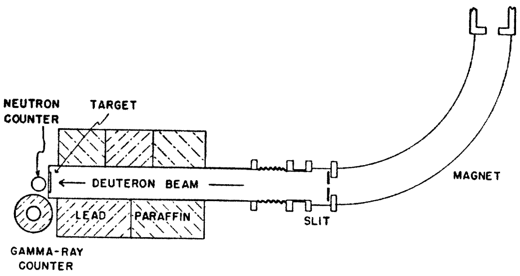

FIG. 1. Target and counter arrangement.

directly down the vacuum tube. The neutron counter was placed in as close proximity to the target as possible for reasons of intensity, insuring a large factor over background. Background counting rates taken with the beam on the low energy side of the slit indicated that the background was always less than 1 percent of the neutron counting rate.

Energy Sensitivity of the Fast Neutron Counters

It has been shown[15] that the sensitivity of a biased proportional counter detecting recoils whose ranges end in the counter depends on energy according to the relation:

$$S(E)=(1-B/E)\sigma(E),$$

where E is the neutron energy, B is the bias energy, and $\sigma(E)$ is the scattering cross section. In the case of argon, the recoil energy in the forward direction is 9.5 percent of the incident neutron energy. The forward argon recoils from beryllium bombarded by 1-Mev deuterons thus have energies from 0.2 to 0.5 Mev and ranges less than a millimeter. With the bias set in the range 500 to 600 kev (50 to 60-kev recoil energy), the values of $S(E)/\sigma(E)$ at 1-Mev bombarding energy are calculated to be 0.6, 0.8, 0.9, and 0.9 for the four Q values ranging from 0.8 to 4.3 Mev in order. Since $\sigma(E)$ is not known, we cannot estimate $S(E)$. It seems likely, however, that the argon counter has a sensitivity of approximately the same magnitude for all four groups and that the argon counter excitation curve gives a true picture of the fast neutron excitation curve.

For bombarding energies below 500 kev the bias was kept fixed. Above 500 kev the bias was increased with deuteron bombarding energy in proportion to the energy of the lowest energy neutron group ($Q=0.8$ Mev), so that the factor $(1-B/E)$ remained constant for that group. This kept the average sensitivity to the four known neutron groups fairly constant, since the sensitivities to the higher energy groups are less bias dependent.

For the hydrogen counter the condition that recoil ranges end in the counter is not fulfilled. This, together with the small bias used (100 kev), results in a sensitivity mainly dependent on $\sigma(E)$ for the known neutron groups. From $\sigma(E)$[16] the relative sensitivities at 1-Mev bombarding energy are calculated as 1.0, 0.7, 0.5, and 0.4 for the four Q values ranging from 0.8 to 4.3 Mev in order. Thus this counter is differentially sensitive to the neutrons of lower energy.

Results

The excitation curve taken with the argon counter is shown in Fig. 3. It is believed to represent the yield of all four fast neutron groups. It shows no sharp resonances, although the same careful check was made with thin targets and high resolution of beam energy as was done for the gamma-radiation. The curve is plotted from data taken with targets 25 to 40 kev thick, with the beam defining slits opened to a width of 10 kev.

Up to 1.4 Mev the curve coincides fairly well with the gamma-ray excitation curve when the two are normalized arbitrarily. Below 800 kev the neutron curve can be fit with a barrier penetration function, indicating that the yield depends primarily on this factor at low energy. A broad resonance located at 1.0 to 1.1 Mev appears necessary to account for the shape of the curve in this region, just as for gamma-rays. The rise in the neutron yield starting at about 1.45 Mev is interpreted as due to neutrons of a new group with negative Q. This last point will be discussed further after considering the hydrogen-counter data.

The excitation curve in the forward direction taken with the hydrogen counter is also shown in Fig. 3. The principal feature is an upward break starting at 950 kev. No corresponding feature occurs at this energy in the gamma-ray curve or the curve for fast neutrons taken with the argon counter, although special check runs were made. A yield curve taken with the hydrogen counter detecting neutrons at an angle of 135° (laboratory coordinate system) with the direction of the incident deuterons shows an upward break at 1135 kev, as plotted in Fig. 4, with the forward yield repeated. (Relative intensities are arbitrary because of difference in geometry.) Taken together, these curves almost certainly indicate the appearance of a new group of neutrons negative Q. Because of the motion of the B^{11} compound nucleus, the neutrons have a higher energy in the forward direction than at 135° and consequently appear above the counter threshold at lower bombarding energy in the forward direction. A counter bias of 95 kev and a Q value of -740 kev are calculated to be consistent with the initial points of rise in the two directions. The relative location of the points of rise depends rather critically on the counter bias, and it is be-

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[15] H. H. Barschall and H. A. Bethe, Rev. Sci. Inst. 18, 147 (1947).

[16] Bailey, Bennett, Bergstralh, Nuckolls, Richards, and Williams, Phys. Rev. 70, 583 (1946).

lieved that this value of 95 kev, which gives good interval consistency among all data available, is the most accurate value we have for the bias. Once the bias is determined the Q value follows. The shape of the rise is what is to be expected from a biased recoil counter, since the factor $(1-B/E)$ rises rapidly with E for small values of $(E-B)$.

For the argon counter the appearance of the group at 1.45 Mev indicates a bias of about 650 kev at that energy. This value is consistent with our estimate of the bias from the size of the gamma-ray pulses. Because of the greater relative sensitivity of the argon counter for fast neutrons with energy well above the bias, the increase in counting rate due to this group would not be pronounced even with considerable intensity.

Another curve taken with the argon counter unexpectedly confirms the existence of this group. The argon counter was surrounded by a slab of paraffin except in the direction of the target. This slab was originally meant to shield against scattered neutrons. However, bigger yields were found with the paraffin, and the yield curve exhibited an upward break at 900 kev. This curve is shown in Fig. 5, arbitrarily normalized below 900 kev to the curve for the argon counter without paraffin. (The yield with paraffin was 40 percent higher at 800 kev before normalization.) A sheet of cadmium 0.80 mm thick completely surrounding the counter wiped out the increase of sensitivity due to the paraffin slabs and the upward break in the curve. The argon counter is, therefore, sensitive to slow neutrons by an unidentified capture process. This process must result in more ionization than that produced by a single electron, since the discriminator bias was set to eliminate pulses from radium gamma-rays. The possibility of protons from a nitrogen impurity has been suggested. In any case, cadmium absorption makes it certain that thermal neutrons are involved, and therefore 900 kev is the threshold at which the new neutron group appears. From this the Q value is also calculated to be -740 kev, in agreement with the value obtained from the hydrogen counter data. The argon counter without paraffin slabs was shielded with cadmium, and a survey made of the energy range from 800 kev to 1500 kev. The results were the same as without cadmium, showing that the thermal neutron sensitivity of the argon counter is not a factor in the data taken without additional paraffin, and that the argon counter without paraffin is counting fast neutrons from the target.

Note Added in Proof: The slow neutron threshold has been confirmed with a proportional counter containing enriched BF_3.

Because of well-known difficulties in the precision measurement of cross sections for neutron emission, we have estimated our thin target cross section from the precision thick target measurements of Amaldi, Hafstad, and Tuve.[2] Integrating our thin target excitation curve for fast neutrons obtained with the argon counter, and using the value given by Amaldi, Hafstad, and Tuve for the total number

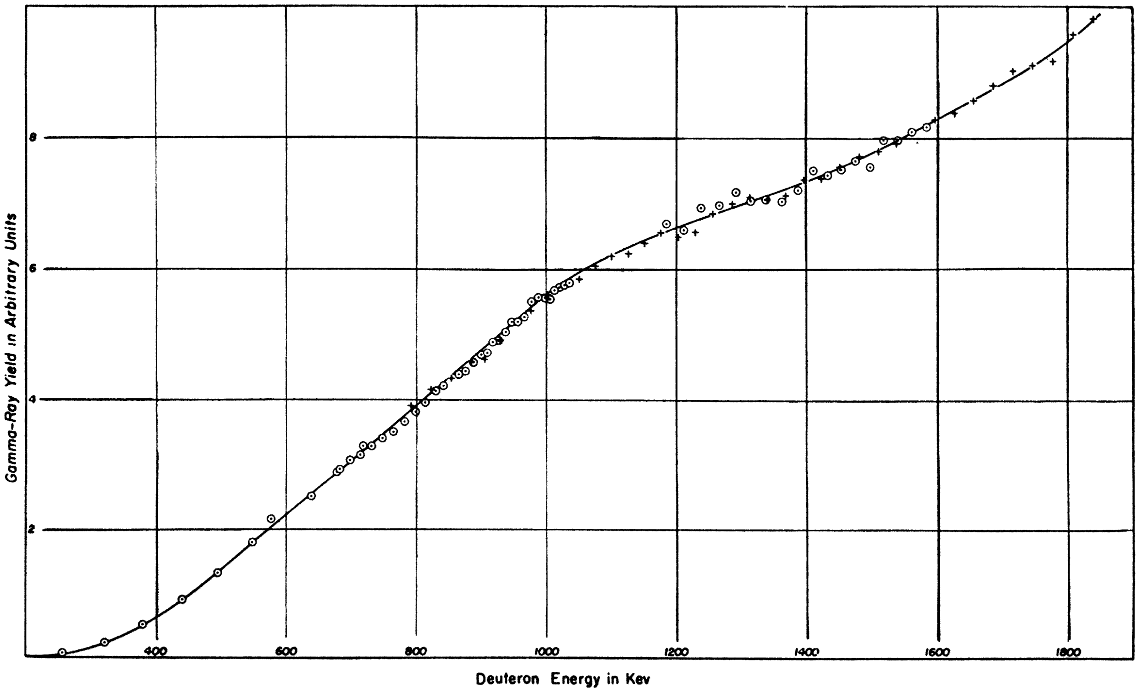

FIG. 2. Excitation curve showing counter counting rate in arbitrary units *vs.* deuteron bombarding energy for the gamma-rays from Be$+d$.

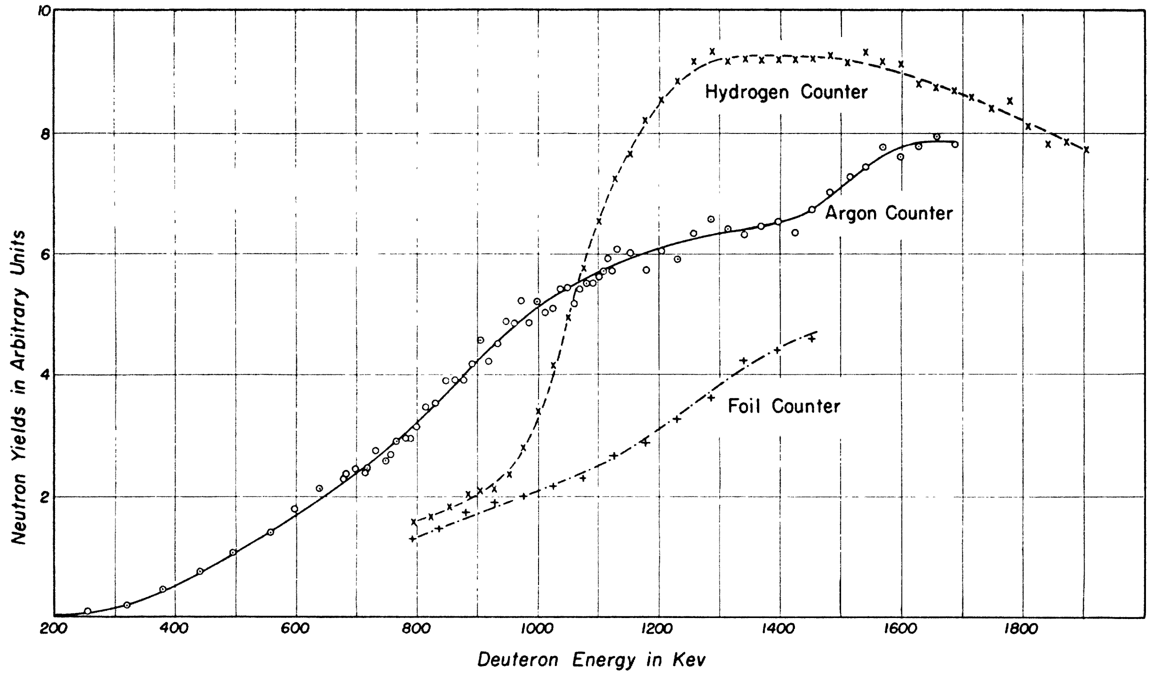

FIG. 3. Excitation curve showing counter counting rate in arbitrary units *vs.* deuteron bombarding energy for the neutrons from Be+d in the forward direction, using argon, hydrogen, and polyethylene foil proportional counters.

of neutrons from a thick target, an estimate of 0.4 barn is obtained for the cross section for total neutron emission at a bombarding energy of 880 kev. In calculating the deuteron penetration of a thick target, a stopping power expression was used which reduced to 1.0 mg/cm^2 Be equal to 1.0 cm of air for 1-Mev deuterons. A check was made at the same bombarding voltage by comparing the neutron emission of thin carbon and beryllium targets of known thickness, using the hydrogen counter with identical geometry. The carbon cross section has been measured accurately by counting the positron from N^{13} formed in the carbon (d,n) reaction.[11] Using the Bethe-Barshall efficiency-energy relation for the hydrogen counter, correcting for differences in angular distribution in the carbon and beryllium neutron emission, and estimating the relative intensities of the Be neutron groups from the number of proton recoils in the cloud chamber of Bonner and Brubaker[4] (estimated to be 31, 37, 15, and 17 percent in order of decreasing Q at 0.9-Mev bombarding energy, after correcting for chamber geometry and scattering cross section), a value of 0.4 barn was obtained by this method also. The second value is possibly subject to a correction to the Bethe-Barshall formula for the lower specific ionization of the higher energy recoil protons in our counter, but the value of 0.4 barn at 880 kev is believed in resonable accord with known data.

It seems reasonable to assume that the variation of the cross section for Be neutrons of positive Q is given up to 1.5 Mev by the argon counter curve. An estimate of the relative intensity of the group of negative Q appearing above 0.9 Mev can be obtained from the hydrogen counter curve when corrections are made for the large proton scattering cross section at low energy and the forward bunching of the neutrons due to motion of the compound nucleus. Two-thirds of the counting rate at 1.4 Mev appears to be due to the low energy group; assuming isotropic emission in the center of gravity coordinate system, this group then con-

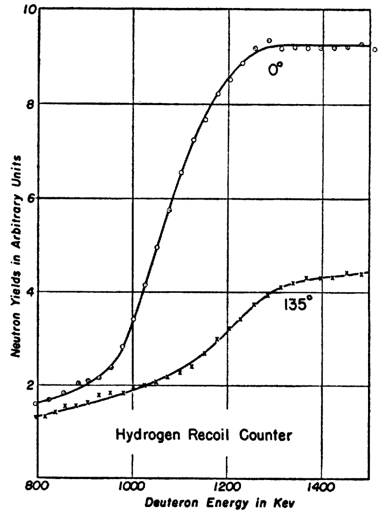

FIG. 4. Comparison of the neutron excitation curve at 135° to the deuteron beam (laboratory coordinate system) with the excitation curve in the forward direction.

stitutes about 0.3 of the total neutron emission at this energy.

ANGULAR DISTRIBUTION OF NEUTRONS

Since particle yields are known to depend on the angular position of the detector with respect to the direction of the incident beam, surveys were made of the angular distribution of the neutrons for several bombarding energies in order to search for possible structure in the yield curve at angles other than 0°. In order to obtain a combination of sensitivity and angular resolution, use was made of a proportional counter with 21 polyethylene foils spaced 0.32 cm apart along the axis of the counter, each foil being equivalent to 5.5 cm air for proton recoils reaching the end of their range in the gaps between the foils. The counter was filled with argon plus 3 percent carbon dioxide at one atmosphere pressure. The counter was operated with the axis directed at the center of the target. Our quoted resolution is equal to the angular width of the nearest foil seen from the center of the target.

Since the stability of this counter over long periods was not nearly as good as that of our gas recoil counters, data for the angular distribution curves were taken in a manner to minimize drift. The same number of counts (640 single neutron counts) was taken at each point. Points were taken in order without repetition at 15° intervals up to the end of the angular range and then repeated in reverse order. The published curves are averages of the data from three to six such two-way runs. Each point on the curves represents at least 3840 single neutron counts with a predicted mean square deviation of about 1 percent.

In order to adjust the ordinates of the successive angular distribution curves to the correct relative heights, yield curves at 0°, 45°, and 135° were taken with this counter. It was not possible to repeat the points in reverse order (decreasing deuteron energy) in these runs because of the delay involved in recycling the magnetic analyzer between successive points. In this case the plotted points are averages of three or more one way runs. Correction for drift was obtained from the trend of successive readings of the same energy. With the data averaged and normalized, points which are common both to the angular distribution and yield curves differ at most by about 10 percent of either value. Therefore, the data is estimated to be accurate to about ±10 percent, although the relative accuracy of points on a single angular distribution curve is believed somewhat better.

Curves of neutron intensity *vs.* bombarding energy at 0°, 45°, and 135° with ±10° resolution are shown in Fig. 6. A curve at 0° with ±20° resolution is included in Fig. 3 for comparison with the argon- and hydrogen-counter curves. The ap-

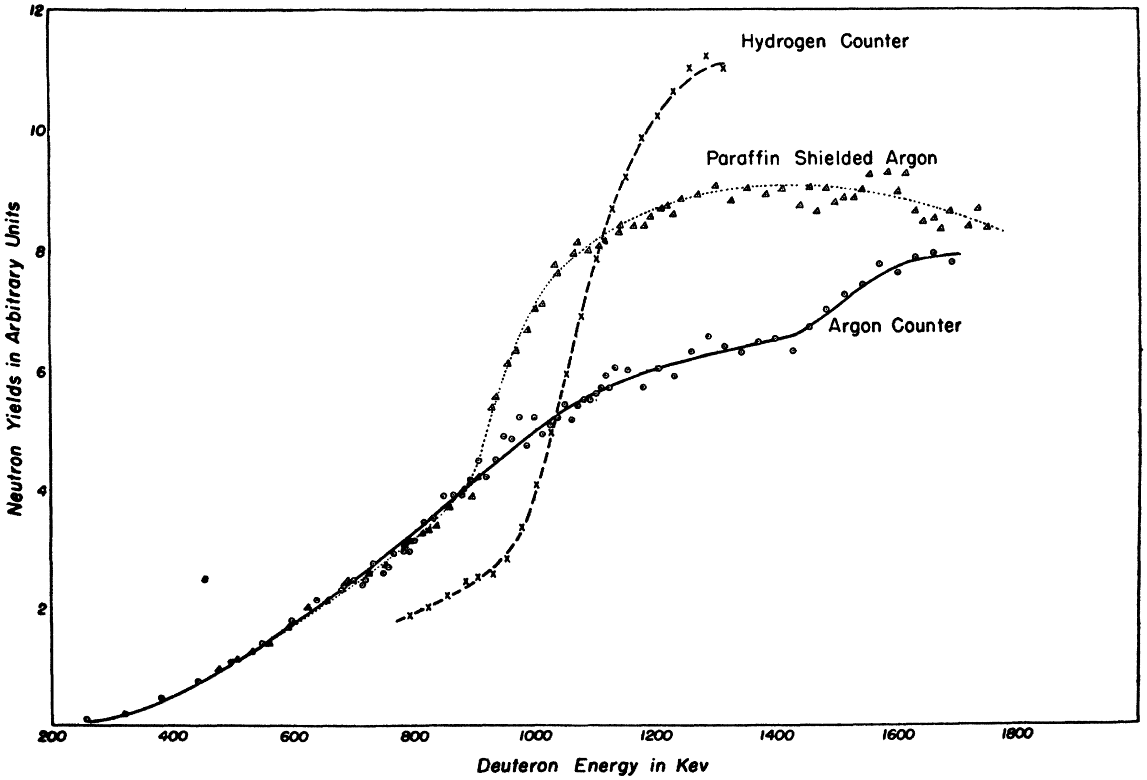

FIG. 5. Comparison of slow-plus-fast with fast neutron excitation curves in the forward direction taken with the argon counter (arbitrarily normalized below 900 kev).

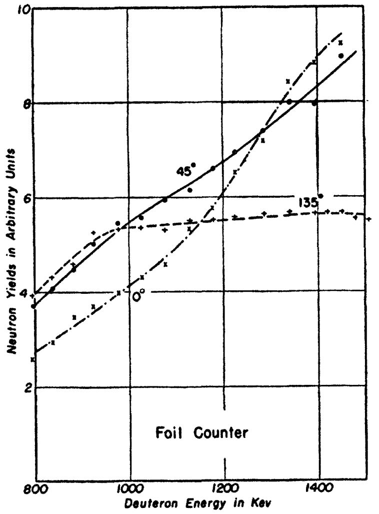

FIG. 6. Neutron excitation curves at 0°, 45°, and 135° to the deuteron beam taken with the polyethylene foil counter (Laboratory Coordinate System).

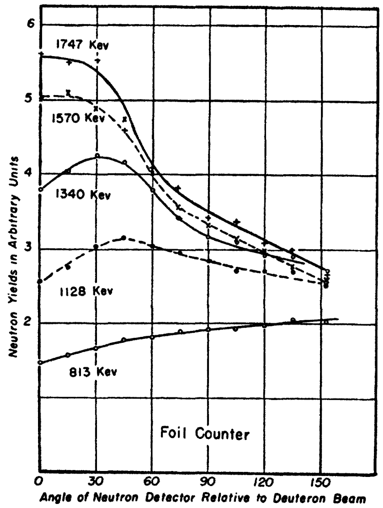

FIG. 7. Distribution in angle of the neutrons from Be+d taken with the polyethylene foil counter (Laboratory Coordinate System).

pearance of the curves in the forward direction indicates that the counter does not quite follow the fast neutron curve about 1.1 Mev but responds increasingly to the low energy group as the bombarding energy increases. Since the counter foils have 5.5-cm air-equivalent thickness for proton recoils reaching the end of their range in the gaps between the foils, the sensitivity would be expected to increase approximately linearly with neutron energy to about 2-Mev neutron energy and to be proportional to the proton scattering cross section for high energy neutrons. The counter response to a low energy group thus does not exhibit the sharp threshold of a gas recoil counter. The experimental yield at 135° is almost constant from 1 to 1.5-Mev deuteron energy with this counter. While the sharpness of the bend between 0.9 and 1.0 Mev is probably experimental error, the 135° curve does indicate a plateau-like leveling off below 1.5 Mev, like the argon-counter curve below 1.4 Mev. The low energy neutron group thus probably does not have sufficient energy at 135° to cause appreciable counter response in this energy range. The 0° and 45° curves lead one to believe that they would exhibit a similar leveling-off tendency above about 1.1 Mev except for the response to the low energy group. This response is, of course, more pronounced for a given deuteron energy at 0° than at 45°.

The angular distribution curves at five bombarding energies are shown in Fig. 7. The resolution is $\pm 9°$ and angles are in the laboratory coordinate system. The points at 75° and 90° have been corrected upward by 8 percent and 16 percent of the plotted values because of longer scattering paths in the target holder at these angles. As a result of the counter characteristics and the presence of a group of negative Q discussed in the previous paragraph, a preponderance of neutrons in the forward direction at the higher bombarding energies does not necessarily indicate asymmetry of emission of the neutrons in the center-of-gravity coordinate system. Since it is not known how much of the forward intensity is due to the low energy group, however, the possibility is not ruled out that the higher energy groups contribute. At 813 kev the backward intensity is somewhat greater than the forward in agreement with the thick target yield of Ageno, Amaldi, Bocciarelli, and Trabachi.[17] While it appears very desirable to apply counting techniques capable of distinguishing between the energy groups in the angular distribution, it seems worth while to include the present data in this report as additional evidence for the presence of a neutron group of negative Q, and as an indication that the absence of narrow resonance structure at 0° is not due to choice of the angular position of the neutron detector but is a characteristic of the reaction.

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[17] Ageno, Amaldi, Bocciarelli, and Trabachi, Atti R. Acad. Italia (Cl. Sci., Fis., Mat.), Series 7, 2, 338 (1940).