the β-rays of radium E as consisting of two types; one slow and one fast. A curve similar to curve B which is somewhat arbitrarily drawn, would show the production of x-rays by the fast β-rays, and curve C, the difference between curves A and B, would show the production of x-rays by the slow β-rays. Evidence in support of this method of interpreting the results has since been obtained here by B. W. Sargent in the course of some careful experiments on the absorption in aluminum of the β-rays of radium E and uranium X.

It is our intention to publish a complete description of the experiments which have led us to adopt the view, held

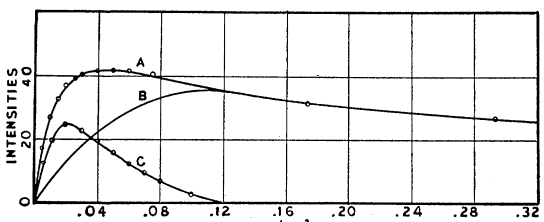

FIG. 2. Production of x-rays in aluminum.

by one of us for many years, that the γ-rays of radium E are, in the main, formed by some of the β-rays as they escape from the nuclei emitting them.

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Low Energy Neutrons from the Deuteron-Deuteron Reaction

In an expansion chamber study of the reaction

$$D+D\rightarrow He^3+n$$

Bonner[1] discovered that the neutrons were not of a single energy. Besides the previously established group of energy 2.50 Mev, a second group of about 1/10 the intensity of the first group and of 1.08 Mev energy was found. Baldinger and his associates,[2] by using an ionization chamber, obtained results in agreement with Bonner's work.

The existence of this low energy group of neutrons suggests that the He^3 nucleus formed simultaneously in the above reaction may be left excited to a level of 1.89 Mev, and a gamma-ray of this energy would be expected when the He^3 falls to its normal state. A search for such a gamma-ray was made by Ruhlig,[3] who found no evidence for it and concluded that not more than one gamma-ray was emitted for every 200 neutrons; this limiting value is in agreement with the work of Kallmann and Kuhn,[4] who studied the deuteron-deuteron reaction by using coincidence counters.

An excited state in He^3 suggests a similar excited level in H^3, but a study of the H^3 and H^1 recoils produced in the above reaction gives no evidence for such a state.[5, 6] The existence of an excited state in either He^3 or H^3 is not in agreement with present nuclear theory, as Share[7] and Schiff[8] have emphasized.

The fact that neutrons also suffer inelastic collisions with heavy nuclei would give rise to neutrons of low intensity spread over a relatively wide range of low energies.[9]

In view of these facts we have made a closer study of the neutrons from the d–d reaction, obtaining 100-kv deuterons with apparatus previously described.[10] The cloud chamber was filled with hydrogen and alcohol vapor and placed about 13 cm from D_3PO_4 target in an aluminum cup, which was substituted for the brass previously used. The low stopping power of the gas in the cloud chamber made it possible to determine whether the low energy neutron spectrum fell to a minimum on the low energy side. Neutrons of energy greater than about two Mev produced recoil protons which passed completely across the chamber.

All proton recoils within 25° of the forward direction which originated in the light beam and within four cm of the chamber wall were tabulated, and 172 such tracks were observed. Of this number, those that remained within the chamber were measured for length and recoil angle. The energies of the low energy neutrons were calculated, and the results are shown in Fig. 1.

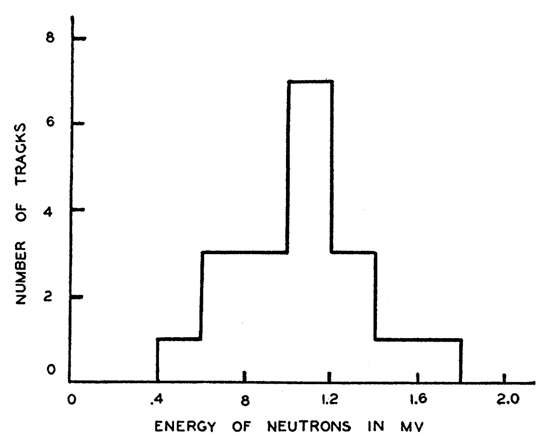

FIG. 1. Low energy neutron spectrum in the deuteron-deuteron reaction.

The stopping power (0.40–0.43) of the gas varies rather rapidly with temperature and with range at low energies; this variation and some uncertainty in determination of recoil angles serve to widen the neutron spectrum found.

The intensity of the low energy group of recoil protons is about $\frac{1}{8}$ that of the high energy group. However, the collision cross section for neutrons of the low energy group, according to the Wigner formula,[11] is approximately twice as great, so that the ratio of the intensities of the two neutron groups is about $\frac{1}{16}$. This neutron group is well defined and of such intensity that it can hardly be ascribed to a group arising from inelastic collisions. The observed energy of 1.1 Mev is in good agreement with Bonner's earlier value.

In order to make certain that the low energy neutrons do not come from some other reaction, photographs were made when deuterons bombarded a target of $H^1{}_3PO_4$. No recoils of any kind were observed.

It would therefore appear that the expected gamma-ray has been overlooked or that other considerations are necessary to explain the low energy neutrons.

We are grateful to Professor H. A. Wilson for his interest and advice and to Dr. T. W. Bonner for many suggestions.

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Note on the Stopping Power of Hydrogen at Very Low Energies

An experiment has been reported recently[1] on the binding energy of the deuteron, as obtained from low pressure ($H^2{}_2-H^2{}_2O$) cloud-chamber observations of proton tracks from photoelectrically disintegrated deuterium. It is desired here to record the information which this experiment yields about the stopping power of hydrogen for (protons of) very low energies.

It can be readily shown that the *average* stopping power of a mixture of n gases at a total pressure P (in cm Hg) is

$$S=\sum_1^n (p_i/76)S_i, \tag{1}$$

$$P=\sum_1^n p_i, \tag{2}$$

where S_i is the *average* stopping power of the ith gas at STP, and where p_i is the partial pressure of the ith gas. By "average" stopping power of a gas, we mean the average value of the stopping power over the path (in the gas) of a charged particle of a given initial energy. For convenience we refer these stopping powers to that of standard air, taken to be unity.

In the experiment mentioned above, $n=2$. Let $i=1$, 2 refer to deuterium and to heavy-water vapor, respectively; then $p_1=P-p_2$. Also, $S_2=S_1+s$, where s is the average stopping power of $\frac{1}{2}O_2$. Thus Eqs. (1) and (2) yield

$$S_1=(76S-p_2s)/P, \tag{3}$$

which is, of course, numerically equal to the average *atomic* stopping power of deuterium relative to the average (atomic) stopping power of air. The experiment mentioned above used $P\cong 8.0$ cm Hg and $p_2\cong 2.7$ cm Hg. Fifteen proton tracks (mean of the initial energies being 0.22 Mev) were observed, having an average length of 2.9 cm; these protons have a range of 0.228 cm in air;[2] therefore, $S=0.228/2.9=0.079$. Substituting in Eq. (3), we thus find

$$S_1\cong 0.35, \tag{4}$$

if we take $s=1.2$.

This value 0.35 for S_1 for (proton) energies $\leqslant 0.22$ Mev appears rather high; but in view of the fact that the stopping power of hydrogen increases[3] from 0.20 at about 3 Mev to 0.25 at about 0.6 Mev, it is probably not much higher than would have been expected. This experimentally determined value of S_1, through the (integral) relation between the energy and range of a particle and the stopping power of the gases through which the particle passes, constitutes a *bound* on the variation of the stopping power of hydrogen with energy for (proton) energies $\leqslant 0.22$ Mev.

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