Gamma-Rays from Boron Bombarded with Protons

We have found a rather weak gamma-radiation emitted when boron is bombarded with protons, and have investigated the spectrum, by measuring the energy of recoil electrons in a cloud chamber. The intensity is certainly not more than 1/10 that obtained from boron bombarded with deuterons under the same conditions, and probably is not far from the upper limit of 1/50 placed upon it by our earlier investigations with an ionization chamber.[1] McMillan[2] has reported radiation from proton bombardment, but no comparison with the deuteron effect can be made from the data he has given.

Fig. 1 shows the energy spectrum of negative secondary electrons obtained from 3000 cloud chamber photographs taken at 900 kv bombarding voltage, 100 microamperes deuteron current and 1500 gauss magnetic field. The glass wall of the chamber was the source of the secondary electrons. The upper curve includes all measurable negative electron tracks, and the lower contains only those which were ejected with an initial angle of less than $7\frac{1}{2}$ degrees with the direction of the incident gamma-radiation. The curves, when corrected according to the theory of Compton collisions, indicate gamma-ray lines at 2.5, 4.2, 5.7, 7.5, 9.8, and 13 (?) MEV. A few high energy pairs were obtained, which are plotted at the bottom of the figure, according to their total energy, which includes the energy equivalent of the rest masses of the two electrons. Each dot represents a pair. The extreme upper limit of the gamma-ray spectrum is probably best given by the pairs, since the probability of pair production increases rapidly with energy, while the number of recoil electrons decreases. The upper limit indicated by the pairs is clearly about 14.5 MEV.

The only reaction involving boron and protons which can release sufficient energy to make possible the emission of the observed 14.5MEV gamma-ray appears to be

$$B^{11}+H^{1}\rightarrow C^{12}. \tag{1}$$

From Bethe's[3] values for the masses of the atoms involved, or, by using the value 13 MEV for the energy released in the reaction

$$B^{11}+H^{2}\rightarrow C^{12}+n^{1} \tag{2}$$

observed by Bonner and Brubaker,[4] and by assuming that the energy contributed by the bombarding proton is approximately 0.9 MEV, we obtain about 15 MEV for the excess energy in reaction (1). This fits well within the accuracy of the experiment, and constitutes perhaps the most unambiguous evidence we have for the simple capture of a proton with the emission of the excess energy entirely as gamma-radiation. This naturally implies that the C^{12} nucleus is capable of existing in an excited state corresponding to 14.5 MEV and of making one or more radiative transitions from this to the normal state, in spite of the fact that the energy it contains is more than sufficient to cause it to split up into three rather energetic alpha-particles; that is, alpha-particles having enough energy to clear easily their mutual potential barrier. This seems to invalidate the argument advanced by Bethe[5] for the maximum value of the mass of C^{12}, namely, that the excitation energy cannot exceed the binding energy of one of the alpha-particles with respect to the other two by more than about 0.7 MEV. The observation of several such high energy gamma-rays from light nuclei has led us to postulate, as suggested in the accompanying letter,[5] that the excitation need not be due entirely to the mutual arrangement or motion of the three alpha-particles, but may consist, at least in part, of excitation within one or more of the alpha-particles themselves, and that this internal alpha-particle energy is not strongly coupled—that is to say, not easily transferred—to the three-alpha-particle system.

The possibility that some of the lower energy lines may arise from the reaction

$$B^{11}+H^{1}\rightarrow 3He^{4}, \tag{3}$$

in which the energy release is about 11 MEV,[6] cannot with certainty be ruled out. The alternative way of accounting for the lower lines is by postulating that the majority of the excited C^{12} nuclei make the transition from the 14.5 MEV level to the ground level by way of intermediate levels. We have not measured quantitatively the excitation curve for the radiation, but the intensity seems to rise considerably more steeply with voltage than is to be expected from the Gamow penetration of the proton alone: it was not possible to obtain appreciable intensity, even of the lower energy lines, at 700 kv. This seems to indicate that all of the radiation is the result of the capture process, although if a very large portion of the energy in reaction (3) were used up in excitation, the three alpha-particles might have a low probability of coming apart through their mutual barrier, and the gamma-rays from this process would in that case also exhibit a high sensitivity to bombarding voltage. The capture of a proton by B^{10} to form the radioactive isotope C^{11} could release as much as 9 MEV, but from the known rate of formation[7] of C^{11} we can be sure that the gamma-rays would be too feeble to account for any of the observed lines. It is reasonable to assume that in reaction (1) the proton is captured only when its kinetic energy is such as to make the total energy of the resulting system correspond just to that of the excited C^{12}; the voltage excitation curve should there-

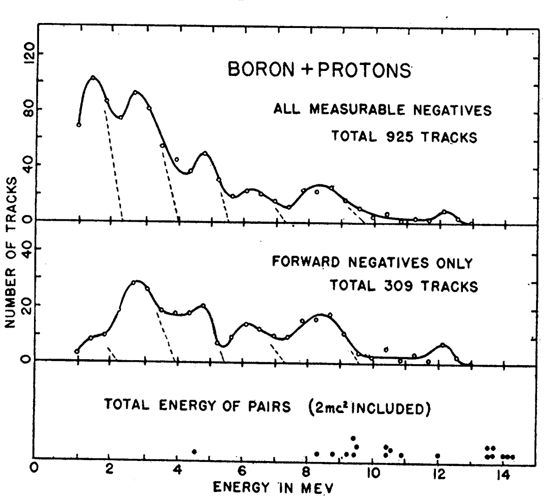

FIG. 1. Recoil electrons and pairs produced by the gamma-radiation from boron bombarded with protons.

fore exhibit a rather sharp maximum, and from the results of our experiments one can estimate that if such a sharp maximum exists it must lie in the neighborhood of the voltage used, namely 0.9 MEV.

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June 14, 1935.

[1] Lauritsen and Crane, Phys. Rev. **45**, 493 (1934).

[2] McMillan, Phys. Rev. **46**, 868 (1934).

[3] Bethe, Phys. Rev. **47**, 633 (1935).

[4] Bonner and Brubaker. Unpublished.

[5] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 100 (1935).

[6] Cockroft, Int. Conf. Phys., London, 1934.

[7] Lauritsen and Crane, Phys. Rev. **45**, 493 (1934); Cockroft, Int. Conf. Phys., London, 1934. Estimates of the efficiency of this process vary among experimenters, possibly because it is a capture process, and is therefore sensitive to bombarding voltage. Our most recent estimate is that, under our experimental conditions at 900 kv, from 100 to 500 C^{11} atoms are formed per second per microampere proton current.

A Note on the Spectra of Jupiter and Saturn

In addition to the many rotation-vibration bands of methane, the spectra of Jupiter and Saturn contain also the harmonic rotation-vibration bands of ammonia at 7920A and 6474A. First photographed in the planetary spectrum by V. M. Slipher,[1] they have since been traced to the ammonia molecule by R. Wildt,[2] and by T. Dunham, Jr.[3]

It is the purpose of this note to show that the bands are of the parallel type; namely, the fourth and fifth harmonics of the fundamental ν_1 at 3337 cm^{-1}.

Employing equivalent path lengths of ammonia up to 315 meter-atmospheres, the bands at 7920A and 6474A were photographed, as was also a band at 5520A.[4] These three bands possess identical structures, indicating that they are harmonics of the same fundamental vibration. In fact, the parallel fundamental at 3337 cm^{-1} and the above bands are connected by the formula:

$$\nu_N = 3389N - 50N^2 - 2N^3,$$

where N is the order of the harmonic.[5]

The structure of the fourth, fifth and sixth harmonics is clearly represented by the photograph and intensity trace shown in Fig. 1.[6] The harmonic bands of ν_1 should each consist of two nearly superimposed bands; that is, the band lines should be double in virtue of the ability of the nitrogen atom to pass through the plane of the hydrogens on its way from one position of equilibrium to the other. Dennison and Uhlenbeck[7] have shown the manner in which the doubling depends upon the amplitude of the nitrogen atom in the case of the harmonic vibrations of ν_3, the second parallel fundamental of ammonia. By applying this analysis to the harmonics of ν_1, a zeroth approximation to the doubling of the state $N\nu_1$ can be obtained. In the vibration ν_1 as opposed to the vibration ν_3 there is considerable motion of the hydrogens in their own plane. This motion renders it more difficult for the nitrogen atom to penetrate the hydrogen plane and thus decreases the doubling of the levels $N\nu_1$ below what it would be for a similar amplitude of oscillation of the nitrogen atom in the motion $N'\nu_3$. A somewhat better approximation can therefore be achieved by reducing the zeroth approximation to one-half or one-third its value. For example, the band $5\nu_1$ should exhibit a doubling in the neighborhood of 15 cm^{-1}. Several such line pairs have been located, but complete ordering of the lines has not yet been accomplished.

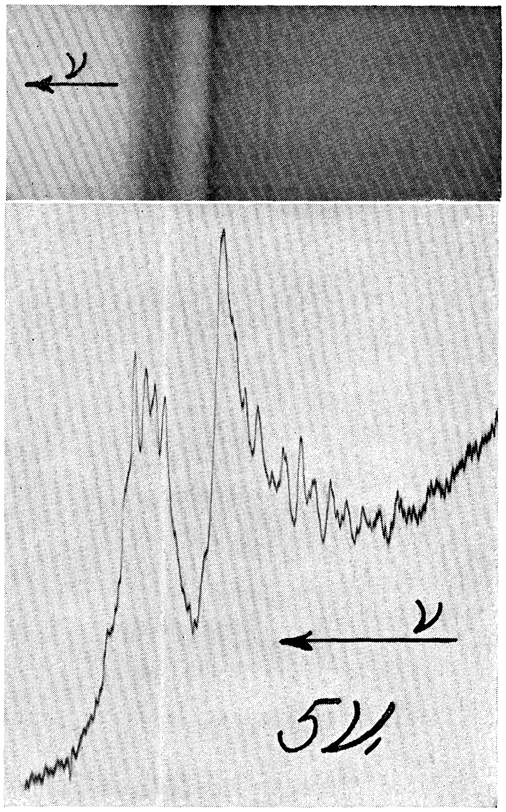

Fig. 1.

Arthur Adel

Lowell Observatory and
University of Michigan,
June 18, 1935.

[1] Slipher, Lowell Observatory Bulletin 42; Popular Astronomy, **37**, 140 (1929).

[2] Wildt, Ver. der Univ. Sternw. zu Gött. Heft 22 (1932).

[3] Dunham, P. A. S. P. **45**, 42 (1933).

[4] For a description of the apparatus see A. Adel and V. M. Slipher, Phys. Rev. **46**, 902 (1934). Eastman P, B and G plates were used.

[5] In the mode of vibration ν_1 the hydrogen nuclei move along median lines of the basal triangle while the nitrogen atom moves along a perpendicular to the plane of the hydrogens. See D. M. Dennison and J. D. Hardy, Phys. Rev. **39**, 938 (1932).

[6] In the present experiment, this band was photographed with a glass Hilger E-I. With higher resolving power, each line seen in the figure splits into several fine ones. See R. M. Badger, Phys. Rev. **35**, 1038 (1930). It appears very likely that this hyperfine structure is caused by the failure to superimpose of the lines:

$$\left.\begin{matrix} J\to J' \\ K\to K \end{matrix}\right\} \begin{matrix} K=0,\,1,\,\cdots J \\ J<J', \end{matrix}$$

in virtue of the differing values of $(1/A-1/C)$ in the ground and excited vibrational states. A and C are, of course, the moments of inertia of the ammonia molecule.

[7] D. M. Dennison and G. E. Uhlenbeck, Phys. Rev. **41**, 313 (1932).