the result is admittedly very approximate, it does show that from the state $J=2$ the predominant process is neutron absorption.

The number given for the mesic absorption probability also represents absorption from the $J=0$ state and is much smaller than the neutron probability. For states of higher J, additional powers of the meson and nucleon momenta appear which make the probability for mesic absorption extremely small. We may, therefore, say that no neutral mesons should be observed, regardless of their parity.

IV. CONCLUSIONS

Preliminary results of the experiment of Panofsky, Aamodt, and Hadley on the absorption of π^- mesons in deuterium[14] indicate a gamma-ray spectrum with a large peak in the neighborhood of 130 Mev, while there is no detectable peak in the spectrum at 70 Mev where the decay quanta from the neutral meson would appear. They estimate that of the total number of absorption events, about $\frac{1}{3}$ actually give rise to gamma-rays. These results are inconsistent with the assumption of either a scalar or vector character for the charged meson but do fit with both the pseudoscalar and pseudovector theories. If the charged meson is assumed to be pseudoscalar, the absence of neutral mesons indicates that they too are pseudoscalar. If, on the other hand, the charged meson is assumed to be pseudovector, nothing can be said about the parity of the neutral meson field.

The author wishes to express his appreciation to Professor R. E. Marshak for having suggested this problem and for his guidance throughout the course of the work. He also wishes to thank Dr. A. S. Wightman for a number of helpful conversations and Professor W. Panofsky for having communicated his new results on the absorption in hydrogen and deuterium.

Note added in proof:—Owing to failure to correct for the $n-p$ mass difference, all energies in Fig. 1 are too high by 1.3 Mev.

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Energy Levels of B^{10}

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The neutron spectrum at 0° and at 80° from the $Be^9(d,n)B^{10}$ reaction has been investigated by means of nuclear emulsions. Energy levels of B^{10} at 0.77, 1.79, 2.22, 3.59, 4.79, 5.12, 5.91, 6.11, 6.57, and 6.81 Mev have been observed as have possible levels at 5.58, 5.68, and 6.38 Mev. There is evidence for multiplicities at 5.12 and, possibly, at 6.11 Mev. No neutron groups were observed which would correspond to levels at 1.4 and 2.85 Mev. This result is in disagreement with the picture of equally spaced levels in B^{10}. An attempt is made to explain the results that led to this picture.

I. INTRODUCTION

In the past few years, much attention has been devoted to the energy levels of B^{10}. The low-lying levels with excitation energies (E_x) of less than 6 Mev have been investigated by means of the reactions $Be^9(d,n)B^{10}$ and $Li^7(\alpha,n)B^{10}$, while the high energy levels ($E_x \geq 6.5$ Mev) have been studied by bombarding Be^9 with protons. Studies of the neutron spectrum by observation of proton recoils in Wilson cloud chambers[1,2] or in nuclear emulsions[3,4] have indicated the presence of levels at approximately 0.7, 2.2, 3.5, and 5.1 Mev above the ground state of B^{10}. Haxel and Stuhlinger[5] have detected neutrons from the $Li^7(\alpha,n)B^{10}$ reaction by means of a boron counter. This work indicated levels at approximately 0.8, 1.3, and 2.1 Mev. Bonner *et al.*,[6] using the method of neutron thresholds to study the neutrons from the $Be^9(d,n)B^{10}$ reaction, have investigated the range from 5 to 6 Mev. They have located levels[7] at 5.098, 5.156, and 5.920 Mev. Rasmussen, Hornyak, Lauritsen, and Chao[8,9] have studied the gamma-rays from the same reaction by means of a magnetic lens spectrometer. They have attributed to B^{10*} gamma-rays of energies 413.5, 716.6, 1022, 1433, 2151, 2871, 3604, 3970, 4470, and 5200 kev, and have assigned corresponding levels to all but the 3970 and the 4470-kev gamma-rays which they assumed to be due to cascade transitions. Rasmussen *et al.*[8,10] state that the levels corresponding to the 716.6, 1433, 2151, 2871, and 3604-kev gamma-rays appear to constitute an equally spaced set of levels leading to the picture of a harmonic oscillator.

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1 T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936).
2 H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).
3 C. F. Powell, Proc. Roy. Soc. (London) **A181**, 344 (1942).
4 W. D. Whitehead and C. E. Mandeville, Phys. Rev. **77**, 732 (1950).
5 O. Haxel and E. Stuhlinger, Z. Physik **114**, 178 (1939).
6 Bonner, Butler, and Risser, Phys. Rev. **79**, 240 (1950).
7 T. W. Bonner, private communication.
8 Rasmussen, Hornyak, and Lauritsen, Phys. Rev. **76**, 581 (1949).
9 Chao, Lauritsen, and Rasmussen, Phys. Rev. **76**, 582 (1949).
10 Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950).

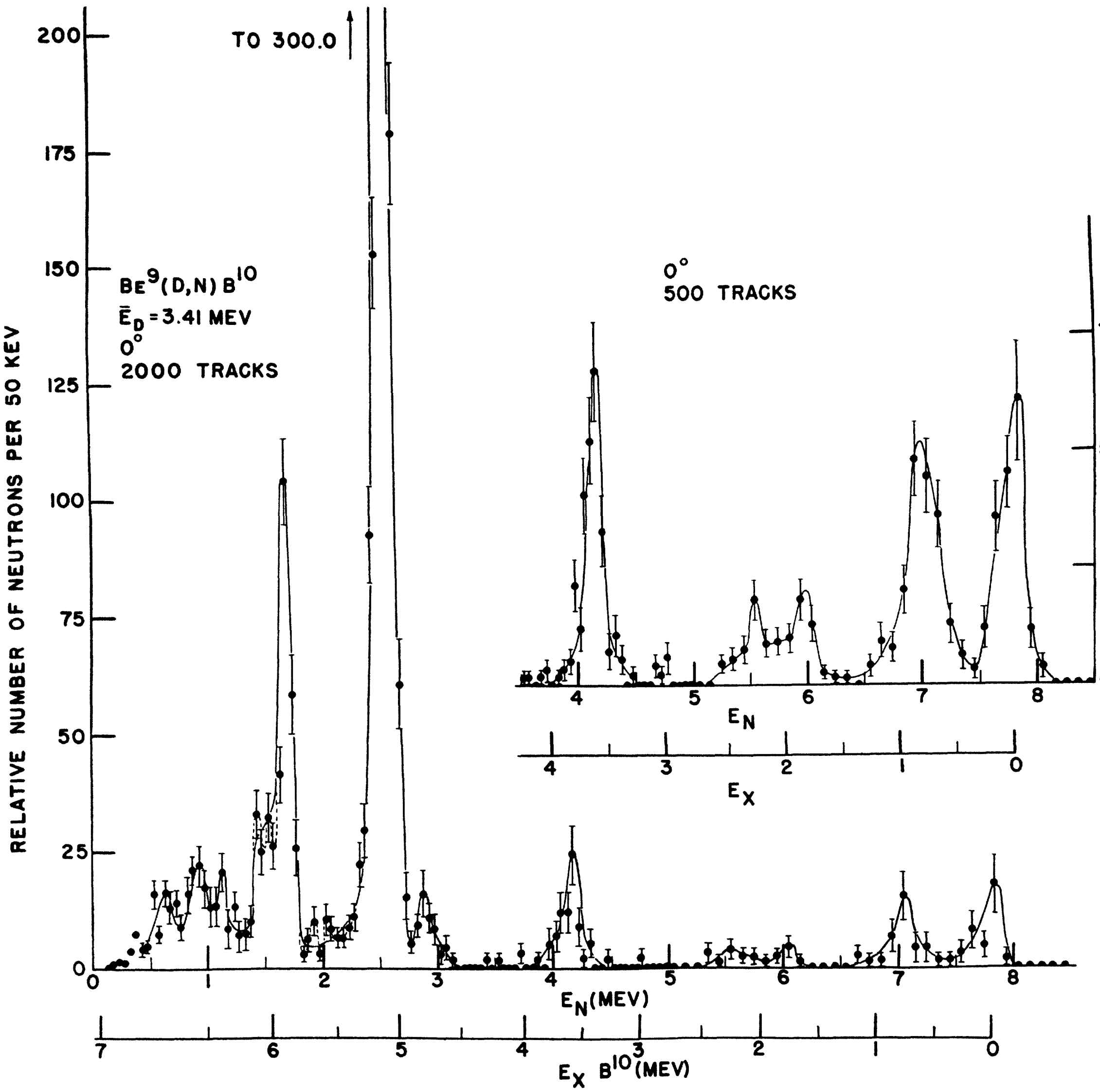

FIG. 1. Relative number of neutrons per 50-kev interval *versus* neutron energy at 0°.

The purpose of this experiment was twofold: (1) to cover, continuously, the energy region from 0 to 7 Mev above the ground state of B^{10} by bombarding beryllium with higher energy deuterons that have been used previously, and, (2) to ascertain whether the assignment of levels to the reported gammas was consistent by obtaining a better resolution for the neutron groups than in previous recoil measurements.

II. EXPERIMENTAL PROCEDURE

A 50-kev thick[10a] foil of beryllium mounted on a tantalum backing was bombarded by 3.436-Mev deuterons from the Wisconsin electrostatic generator. The resultant neutron spectrum was observed by means of 200μ Eastman NTA nuclear emulsions mounted 10 cm from the target and at angles of 0° and 80° to the direction of the beam. In addition, background plates were exposed to deuterons hitting bare tantalum. The criteria for the measurements of the recoil proton tracks have been discussed previously.[11] The neutron energies are calculated from the energies of the proton recoils and from the angles which these recoils make with the incident neutrons. The range-energy relation used in this experiment was found as follows: from previous work,[11,12] the range-energy relation was known for low energy proton tracks ($E_p \leq 2.5$ Mev). The value (7.76 Mev) for the average neutron energy ($\bar{E}_n$) corresponding to the ground state of B^{10} was calculated

[10a] For deuterons of 3.4-Mev energy.

[11] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).

[12] Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **79**, 187 (1950).

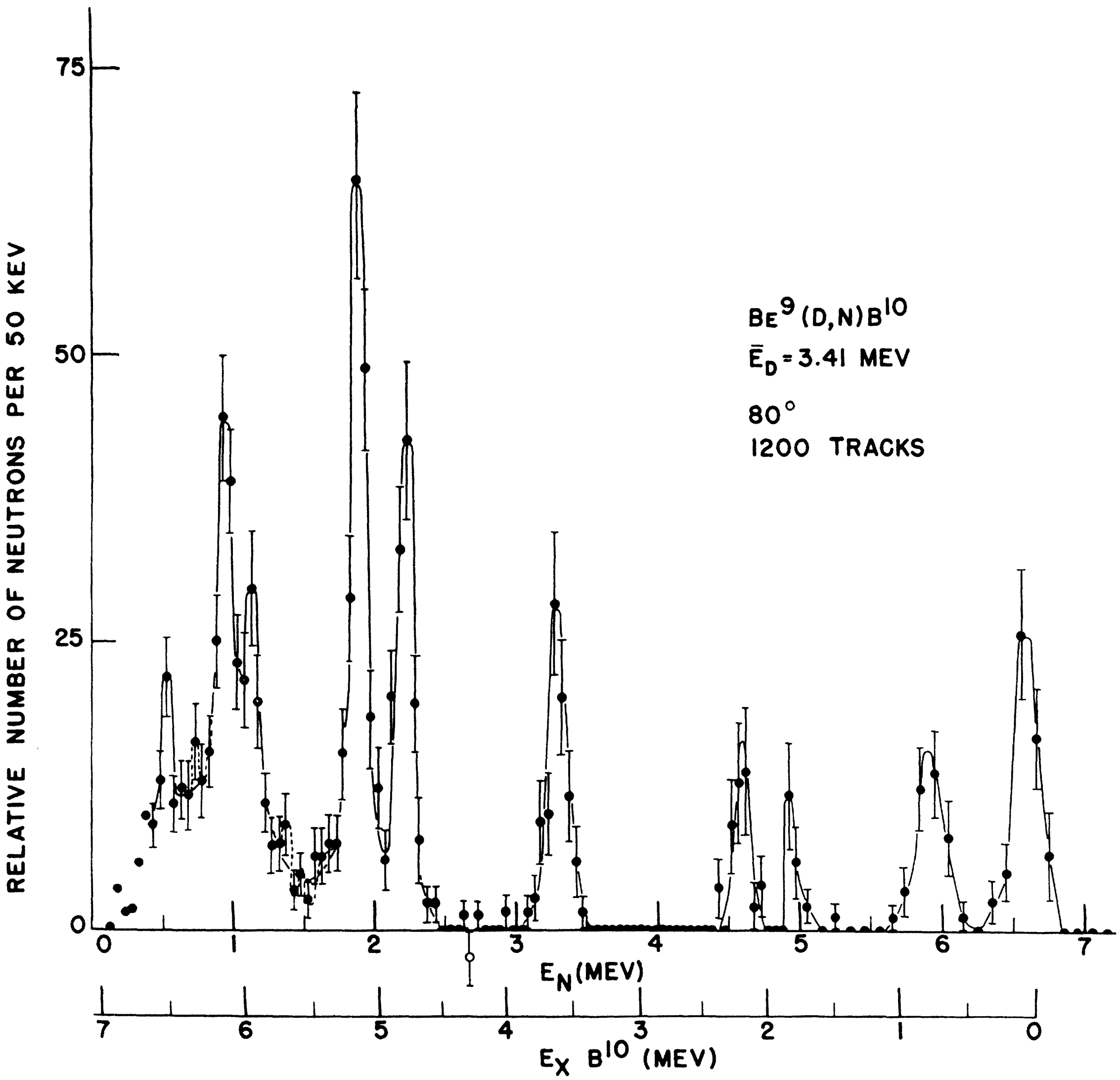

FIG. 2. Relative number of neutrons per 50-kev interval *versus* neutron energy at 80°.

using[13] $Q=4.35$ Mev. A mean value (390 microns) of the ranges of the ground-state tracks which were observed was assumed to correspond to this value of $\bar{E}_n$. The low energy range-energy curve was then extrapolated to this point with a shape similar to that of the Lattès curve.[14] At high energies, this curve is approximately 4.5 percent higher (i.e., 4.5 percent lower energy for a given range) than the Lattès curve for Ilford emulsions. The agreement between the values of $\bar{E}_x$ for groups at 0° and 80° is quite good. $\Delta(\bar{E}_x)$ is ≤ 40 kev, and the average $\Delta(\bar{E}_x)$ for all levels is approximately 20 kev. Taking into account the differences between our values and the more accurate gamma-ray values observed by Rasmussen *et al.*[8] and the uncertainty in the range-energy curve, it is felt that the value of E_x for levels below 3 Mev is known to better than ± 100 kev and to better than ± 50 kev for the levels of higher energy.

Two thousand tracks have been measured on the 0° plates and 1200 on the 80° plates. In order to improve the statistics for high energy neutrons at 0°, an additional 382 tracks, due to neutrons of energy greater than 3.5 Mev, have been measured. The data, corrected for variation of neutron-proton scattering cross section,[15] geometry,[16] and background, is shown as Fig. 1 for 0° (the inset shows the high energy data, including the 382 additional long tracks which were measured), and Fig. 2 for 80°.

Figure 3 shows the distribution of the background tracks at 0° and at 80°. The data have been corrected

[13] Tollestrup, Fowler, and Lauritsen, Phys. Rev. **78**, 372 (1950).
[14] Lattès, Fowler, and Cuer, Proc. Phys. Soc. (London) **59**, 883 (1947).
[15] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[16] H. T. Richards, Phys. Rev. **59**, 796 (1941).

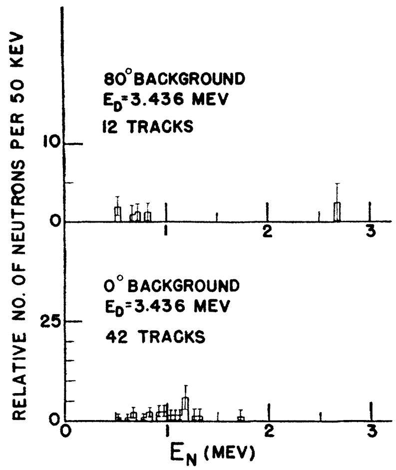

FIG. 3. Background at 0° and at 80°.

for variation of the n–p scattering cross sections and geometry in the same way as the data shown in Figs. 1 and 2. The data have also been corrected for area, since only half of the equivalent area at each angle was scanned on the background plates. Thus, the number of tracks of a given energy was multiplied by two for the area correction. The correction for background has not affected materially the location or intensity of any of the significant neutron groups.

From previous work by the same observer,[12] the width at half-maximum for a neutron group at 2 Mev, using the emulsion technique, is approximately 100 kev. It is not known exactly how the resolution changes for higher or for lower energies. The present data seem to indicate that the width at half-maximum increases with the energy of the group, but that it is less than 300-kev for 8-Mev neutrons. Taking into account straggling, the thickness of the target, the size of the source and the scanning area, and multiple scattering effects, a calculated width for 8-Mev neutrons, at half-maximum, of approximately 200 kev is obtained. The reason for the larger observed width is not understood. The data has been plotted in 50-kev intervals for neutrons of energies less than 5 Mev, and in 100-kev intervals for higher energy neutrons.

TABLE I. Intensities of the neutron groups at 0° and at 80° (lab) in the center-of-mass system.

Level at:	Relative intensity at 0°	Relative intensity at $\phi°$	$\phi°$	Ratio 0°/$\phi°$
0	15	10	85.5	1.5
0.77	14	7	85.6	2.0
1.79	3	2	85.7	1.5
2.22	5	4	86.0	1.2
3.59	14	8	87.2	1.7
4.79	10	12	89.1	0.8
5.12	195	19	90.0	10.0
5.58	4	1	91.2	4.0
5.68	4	3	91.5	1.4
5.91	37	7	92.5	5.3
6.11	20	13	94.0	1.5
6.38	11	4	96.8	2.8
6.57	12	6	99.1	2.0
6.81	8			

III. EXPERIMENTAL RESULTS

A secondary scale, showing the excitation energy (E_x) of the B^{10} nucleus, has been drawn on both Figs. 1 and 2 so that the value of the energy level corresponding to a given neutron group can be seen directly.

The ground state and a level at 0.77 Mev can be seen clearly. There are no neutron groups at either 0° or 80°, however, corresponding to a level at 1.4 Mev. The two neutron groups at 6.00 and 5.55 Mev (0°) and at 4.95 and 4.60 Mev (80°) should be noticed. These two groups correspond to at least two levels whose energies would be 1.79 and 2.22 Mev. No neutron groups were observed which would correspond to a level at 2.85 Mev. The known level at 3.59 Mev is observed again.

The neutron groups at 2.90 Mev (0°) and 2.20 Mev (80°) correspond to a level at 4.79 Mev. Whitehead and Mandeville,[4] using 1.15-Mev deuterons, observed a proton recoil group at about 0.70 Mev which might correspond to this 4.79-Mev level. However, they assign this group to neutrons from the $C^{12}(d,n)N^{13}$ reaction. Their data for deuterons of high energy (1.62 Mev) do not show any groups due either to carbon contamination or to the 4.79-Mev level. The target used by Whitehead and Mandeville was thicker (100 kev) than the one used in this experiment, and apparently their resolution was poorer. Bonner[7] states that he has not yet taken accurate threshold measurements below 730 kev and therefore has no evidence on this point at all. The threshold for the 4.79-Mev level would be at approximately 525 kev.

The neutron group at approximately 2.55 Mev (0°) and at approximately 1.88 Mev (80°) corresponds to the known, but here unresolved, doublet at 5.098 and 5.156 Mev.[7] Although the doublet is not resolved at 0°, the large half-width of this peak and its high intensity may indicate the presence of several closely spaced levels. It is interesting to note that the half-width of the corresponding peak at 80° is smaller by a factor of two. It should also be noticed that this neutron group is very definitely bunched forward in the center of mass system (Table I).

If the groups at $\bar{E}_n=2.05$ Mev and 1.92 Mev (0°) and $\bar{E}_n=1.47$ and 1.37 Mev (80°) are real, levels at 5.58 and 5.68 Mev are indicated. The neutron groups at 1.68 Mev (0°) and 1.12 Mev (80°) correspond to a level at 5.91 Mev which has been observed, independently, by Bonner, though he finds no evidence for levels at 5.58 and 5.68 Mev.[7] The groups with $\bar{E}_n=1.48$ Mev (0°) and 0.94 Mev (80°) correspond to a level with $\bar{E}_x=6.11$ Mev. The width at half-maximum, larger than expected for a single level, may indicate a doublet.

Other high energy levels undoubtedly exist, but the interpretation of the data is not clearcut owing to poorer statistics. The following is a tentative interpretation of the data obtained at both 0° and 80°: (1) A possible level at 6.38-Mev excitation. (2) A probable level at 6.57-Mev excitation. (3) The known level[17] at 6.81 Mev would correspond to the neutron group observed at approximately 0.62 Mev at 0°. The corresponding group at 80° would have an energy less than 0.5 Mev and, therefore, could not be observed reliably by this method.

Table I shows the relative intensities in the center-of-mass system of the neutron groups observed at laboratory angles of 0° and 80°. The same table also shows the ratio of the intensities at 0° to that at ϕ, where ϕ is the center-of-mass angle for the given group corresponding to the laboratory angle of 80°. Only a few of the neutron groups show a large difference in intensity at the two observation angles in the center of mass system. The data for 80° will correspond qualitatively to the total cross section because of the small anisotropy and the large solid-angle weighting factor.

No neutron groups were observed which would correspond to ground-state neutrons from the reactions (1) $H^2(d,n)He^3$ (these neutrons would appear at 6.6 Mev at 0° and at 3.7 Mev at 80°), (2) $C^{12}(d,n)N^{13}$ (3.1 Mev —0°—and 2.5 Mev—80°), and (3) $O^{16}(d,n)F^{17}$ (1.7 Mev —0°—and 1.4 Mev—80°).

IV. DISCUSSION

Because a high bombarding energy was used, deuterons of high angular momentum would be effective in forming states of a wide range of angular momenta and of either parity in the compound nucleus. Since the excitation of the compound nucleus is approximately 19 Mev, one expects a large density of overlapping levels in that nucleus. Hence, it is difficult to see why there should not be neutron groups corresponding to all existing levels of B^{10}. The fact that no neutron groups were observed which would correspond to levels at 1.4 and 2.85 Mev appears, therefore, to be strong evidence that the picture of equally-spaced levels in B^{10} is incorrect.

Still, it is necessary to account, in some way, for the gamma-rays observed by Rasmussen, Hornyak, Lauritsen, and Chao. Figure 4 shows a possible level scheme which is consistent with our neutron data and

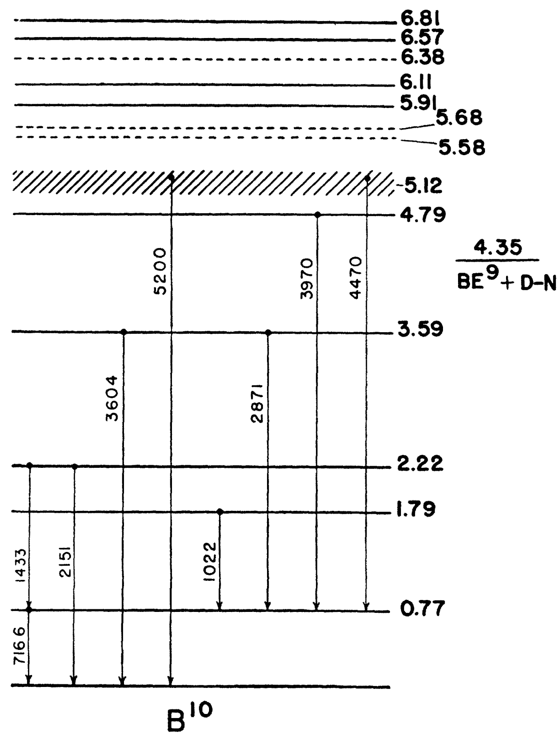

FIG. 4. Energy level diagram of B^{10}.

with all gamma-rays observed by Rasmussen *et al.*, except possibly for the 413.5-kev gamma-ray. The 413.5-kev gamma-ray may result from the transition between the 2.22- and the 1.79-Mev levels. However, it is somewhat surprising that this gamma-ray competes successfully in intensity with the 1433- and the 2151-kev gamma-rays.

One of the results of the transitions suggested in Fig. 4 is that the 716.6-kev gamma-ray should be relatively very intense, since several of the other gamma-rays are explained as cascades to the 0.77-Mev level. This appears to be the case.[10]

The author is extremely grateful to V. R. Johnson for his assistance in the exposure of the plates, and to Professor H. T. Richards, who suggested this problem and whose criticisms and suggestions throughout all stages of this work were invaluable.

[17] Thomas, Rubin, Fowler, and Lauritsen, Phys. Rev. **75**, 1612 (1949).