Neutrons from the Breakup of He^5

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(Received March 9, 1939)

The energy spectrum of the neutrons from the disintegration of lithium by 0.8-Mev deuterons has been measured by the method of recoil particles in a high pressure cloud chamber at different stopping powers. A sharp drop in the number-energy curve at 3.8 Mev is interpreted as indicating the maximum energy of the neutrons from the two-stage reaction

$$Li^7+D^2\rightarrow He^4+He^5+14.3\text{ Mev}, \quad (1)$$

$$He^5\rightarrow He^4+n^1+0.8\text{ Mev}. \quad (1.0)$$

By measuring the alpha-particle spectrum with an ionization chamber-linear amplifier-counter, the relative number of alpha-particles from (1) gave the relative probability of reaction (1) and hence (1.0) in good agreement with the observed relative number of neutrons.

INTRODUCTION

THE investigation of the energy spectrum of the neutrons from the disintegration of lithium by deuterons is made difficult by the number of reactions taking place and the lack of homogeneity of the emitted neutrons. The following is a summary of the Li(d, n) reactions

$$Li^7+D^2\rightarrow He^5+He^4+14.3\text{ Mev}, \quad (1)$$

$$He^5\rightarrow He^4+n^1+0.8\text{ Mev}, \quad (1.0)$$

$$Li^7+D^2\rightarrow Be^8+n^1+15\text{ Mev}, \quad (2.1)$$

$${}^*Be^8+n^1+12\text{ Mev}, \quad (2.2)$$

$${}^{**}Be^8+n+5\text{ Mev}, \quad (2.3)$$

$$[Li^7+D^2\rightarrow He^4+He^4+n^1+15.1\text{ Mev}, \quad (3)]$$

$$Li^6+D^2\rightarrow He^5+He^3+0.8\text{ Mev}, \quad (4)$$

$$He^5\rightarrow He^4+n^1+0.8\text{ Mev}, \quad (4.0)$$

$$Li^6+D^2\rightarrow Be^7+n^1+3.1\text{ Mev}, \quad (5)$$

$$[Li^6+D^2\rightarrow He^4+He^3+n^1+1.6\text{ Mev}. \quad (6)]$$

Neutrons from these reactions were first observed by Crane, Lauritsen and Soltan.[1] Their energy was measured by Bonner and Brubaker,[2] who observed an apparent inhomogeneity of the neutrons except for one group of mono-energetic neutrons giving evidence for the reaction

$$Li^7+D^2\rightarrow Be^8+n^1+15\text{ Mev}, \quad (2.1)$$

where Be^8 is left in its lowest (slightly unstable) level.[3] Later observations gave evidence for the same reaction with Be^8 left in a wide three-Mev level.[4]

$$Li^7+D^2\rightarrow {}^*Be^8+n^1+12\text{ Mev}. \quad (2.2)$$

Rumbaugh, Roberts and Hafstad[5] have observed neutrons from Li^6 separated targets and have also found evidence for the formation of Be^7 indicating the reaction

$$Li^6+D^2\rightarrow Be^7+n^1+3.1\text{ Mev}. \quad (5)$$

In addition to these more or less discrete groups of neutrons, there have also been observed neutrons of apparently inhomogeneous energies from both Li^6 and Li^7 targets. These have usually been ascribed to the three-particle reactions

$$Li^7+D^2\rightarrow He^4+He^4+n^1+15.1\text{ Mev} \quad (3)$$

and $$Li^6+D^2\rightarrow He^4+He^3+n^1+1.6\text{ Mev}. \quad (6)$$

While this mechanism of disintegration may

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[1] Crane, Lauritsen and Soltan, Phys. Rev. **44**, 692 (1933).

[2] T. W. Bonner and W. M. Brubaker, Phys. Rev. **48**, 742 (1935).

[3] O. Laaf, Ann. d. Physik **32**, 743 (1938) has recently detected the coincidences of the alpha-particles from

$$Be^8\rightarrow He^4+He^4+<0.1\text{ Mev}. \quad (2.01)$$

[4] W. E. Stephens, Phys. Rev. **53**, 223 (1938). $^*Be^8$ has been observed in other reactions: $B^{11}+H^1\rightarrow {}^*Be^8+He^4+5.8$ Mev, Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **150**, 241 (1935); P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **154**, 279 (1936); and $B^{10}+D^2\rightarrow {}^*Be^8+He^4+15$ Mev, J. D. Cockcroft and W. B. Lewis, Proc. Roy. Soc. **154**, 246 (1936).

[5] Rumbaugh, Roberts and Hafstad, Phys. Rev. **54**, 657 (1938).

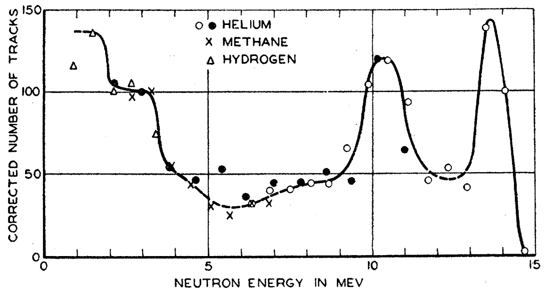

FIG. 1. Energy distribution of the neutrons from lithium bombarded with deuterons. The energy of the neutrons was measured by recoils in helium and hydrogen and the relative intensities corrected for geometry of the cloud chamber and scattering cross sections.

occur, it seems more reasonable to consider the reaction as mainly occurring in two stages

$$Li^7+D^2\rightarrow Be^8+n^1, \qquad (2)$$

$$Be^8\rightarrow He^4+He^4, \qquad (2.0)$$

and to consider the additional modes of disintegration[6]

$$Li^7+D^2\rightarrow He^5+He^4+14.3\ \text{Mev}, \qquad (1)$$

$$He^5\rightarrow He^4+n^1+0.8\ \text{Mev} \qquad (1.0)$$

and

$$Li^6+D^2\rightarrow He^5+He^3+0.8\ \text{Mev}, \qquad (4)$$

$$He^5\rightarrow He^4+n^1+0.8\ \text{Mev}. \qquad (4.0)$$

With this in mind, we reinvestigated the neutron spectrum resulting from the bombardment of lithium with deuterons to see if more accurate data would give any indications for reaction (1.0) and higher levels of Be^8. Preliminary results were reported in abstracts of the San Diego meeting of the American Physical Society.[7]

[6] Especially since the existence of reaction (1) has been established by Williams, Shepherd and Haxby, Phys. Rev. **52**, 390 (1937).

[7] H. Staub and W. E. Stephens, Phys. Rev. **54**, 236 (1938) and W. E. Stephens and H. Staub, Phys. Rev. **54**, 237 (1938).

EXPERIMENTS

Neutrons.—In measuring the neutron spectrum, we have followed the procedure already described[8] with one exception. The stopping power in each run was determined by replacing the Li target by a D_3PO_4 target and measuring the DD neutron recoils under the same conditions as the lithium neutron recoils. In calculating these stopping powers, the usual corrections[9] were applied to the extrapolated range of the DD neutron recoils as found in the cloud chamber, and this mean range was divided into the range as calculated from Bonner's[10] Q value of 3.29 Mev. The variation of stopping power with energy was taken from Livingston and Bethe[11] for hydrogen and methane and from Mano[12] for helium. The Cornell range-energy curves were used (revised 1938). The correction which was applied to the observed number of tracks for geometry was

$$K=(\pi/2)[\sin^{-1}\{1-(T/D)^2\}^{\frac{1}{2}} -(T/D)\{1-(T/D)^2\}^{\frac{1}{2}}]^{-1},$$

where T is the track length and D is the diameter of the cloud chamber. The neutron-proton scattering cross section was taken from Wigner's formula with $\epsilon_1=0.12$ Mev and $\epsilon_2=2.19$ Mev.[13] At high energies, the value of $(\sigma_{He}/\sigma_H)_{back}$ was assumed to be near unity.[14] The number of tracks

[8] W. M. Brubaker and T. W. Bonner, Rev. Sci. Inst. **6**, 143 (1935); T. W. Bonner and W. M. Brubaker, Phys. Rev. **47**, 910, 973 (1935); **48**, 742 (1935); **49**, 19 (1936); **50**, 308 (1936); Stephens, Djanab and Bonner, Phys. Rev. **52**, 1079 (1937); W. E. Stephens, Phys. Rev. **53**, 223 (1938).

[9] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 289 (1937).

[10] T. W. Bonner, Phys. Rev. **53**, 711 (1938).

[11] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 274 (1937).

[12] G. Mano, J. de phys. et rad. **5**, 628 (1934).

[13] $\sigma=5.15\times10^{-24}[\frac{1}{4}(\epsilon_1+E/2)^{-1}+\frac{3}{4}(\epsilon_2+E/2)^{-1}]$.

[14] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).

TABLE I. *Relevant data for the experiments on neutron energy distribution.*

Gas	Pressure Atmos.	Stopping Power: For $D(d, n)$ Recoils	Stopping Power: For ThC′ αs	Deuteron Bombarding Energy Mev	No. of Pictures	No. of Tracks	Energy Range Covered Mev
Methane	11.6	11.5		0.8	5,000	1,026	3 to 7
Hydrogen	12.5	2.89		1.0	2,500	714	1 to 3
Helium	6.3	1.38		0.8	12,000	746	3 to 10
Helium	11.9		2.6	0.93	9,000	1,034	7 to 15
				Total	28,500	3,520	1 to 15

counted was first changed from range intervals to energy intervals and then corrected for geometry and cross section. The resulting number-energy curves were then fitted at about three Mev and six Mev and gave Fig. 1. Table I gives the relevant data on the different runs. Included in this are the data taken with high pressure helium already reported.[4] The different runs were made in order to cover the whole spectrum most conveniently and the different runs were overlapped sufficiently to eliminate uncertainties in corrections.

Alpha-particles.—To make sure that reaction (1.0) was probable enough at our bombarding energies to be observable, we have measured the number range curve for the alpha-particles from lithium disintegrated by 0.8-Mev deuterons.[15] An absorption chamber was placed between the target and a four-mm ionization chamber. This latter was coupled to a linear amplifier of the Wynn-Williams type.[16] The output was put through a biased single thyratron to actuate a telephone counter. As the resolving power of the counter was about 300 counts per minute, care was taken that the counting rate was low compared to this. Special care was taken to make the mechanical coupling of the chamber to the target

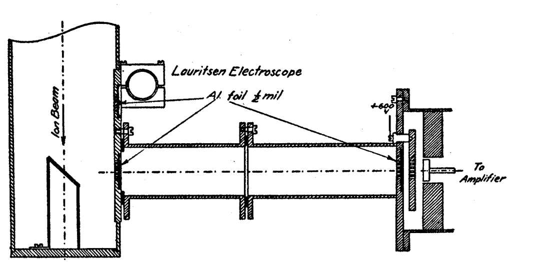

FIG. 2. Diagram of target tube, absorption tube, ionization chamber and monitor electroscope for measuring the number-range curve for the α-particles from lithium bombarded with deuterons.

tube insensitive to the vibration of the target tube, which thus prevented an increase in the counter noise level.

The absorption chamber was calibrated with ThC and C′ and Po alpha-particles. With the Po alpha-particles, number-bias curves for different

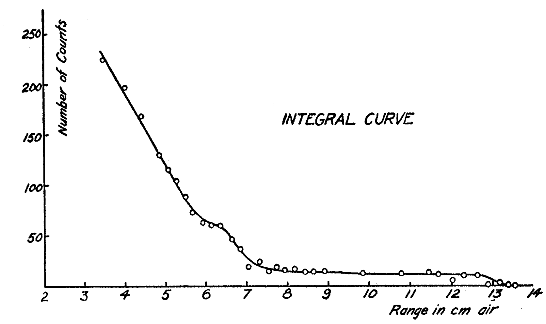

FIG. 3. Integral number-range curve of the α-particles from lithium bombarded with deuterons.

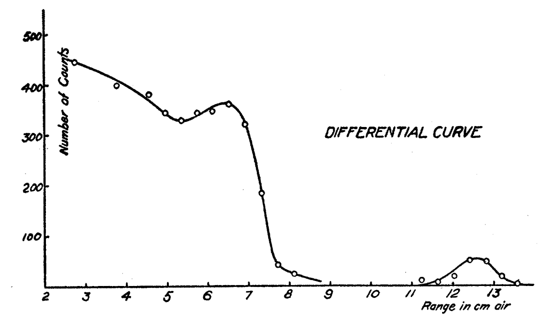

FIG. 4. Differential number-range curve of the α-particles from lithium bombarded with deuterons.

absorption were run to determine the bias for maximum ionization,[17] and it was determined that for differential counting the bias was about 98 percent of this maximum bias. For integral counting, the bias was put at 36 percent of the maximum and all particles entering the chamber were counted. The noise level was estimated to be about nine percent of the maximum alpha-particle ionization.

As a measure of primary intensity, we have used a Lauritsen electroscope[18] with a small ionization chamber mounted as shown in Fig. 2. Alpha-particles of over four cm range coming from the target could enter the electroscope and gave a deflection proportional to the total number of alpha-particles. By interposing foils between the electroscope and target it was found that most of the ionization in the electroscope was due to alpha-particles from the target. Because of the small size of the electroscope chamber, the effect of x-rays, γ-rays, etc., was

[15] This curve is similar to Williams, Shepherd and Haxby, reference 6, but taken at our higher bombarding energy.

[16] Baldinger, Huber and Staub, Helv. Phys. Acta **11**, 247 (1937).

[17] A very clear discussion of these procedures is given in M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

[18] C. C. Lauritsen and T. Lauritsen, Rev. Sci. Inst. **8**, 438 (1937).

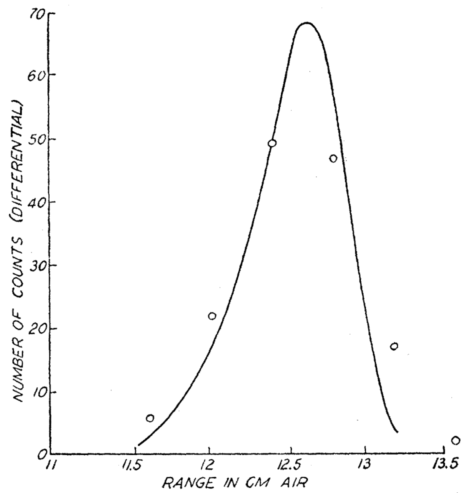

FIG. 5. Differential number-range curve for the α-particles from Li^6+D^2. The experimental points are from Fig. 4. The curve is calculated by taking into account penetration in the target and straggling.

small. Hence the alpha-particle-number-range curve was obtained by determining the number of counts at a given pressure in the absorption cell for a standard deflection of the electroscope. This deflection corresponded to about 3000 alpha-particles. Both an integral and a differential curve were taken and are shown in Figs. 3 and 4. The seven-cm group of alpha-particles ascribed to the reaction

$$Li^7+D^2 \rightarrow He^5+He^4+14.3 \text{ Mev} \qquad (1)$$

is not completely resolved, but is clearly evident. Its width is greater than that found by Williams, Shepherd and Haxby[6] because of the increased energy of the incident deuterons which gives a greater energy spread in the disintegrating deuterons (and a possible difference in chamber depth and percent bias). A calculation of the distribution in range of the 13-cm group of alpha-particles based on Eq. (801) of Livingston and Bethe[9] gives the curve of Fig. 5. The experimental points fit quite well, indicating the line is no wider than would be expected. A reasonable guess at the shape of the seven-cm group gives a width slightly greater than that of the 13-cm group in agreement with Williams, Shepherd and Haxby[6] and probably indicates a natural width of the level in He^5 of the order of 0.1 or 0.2 Mev. The alpha-particle intensities and ranges taken from these curves are shown in Table II.

This ratio of 1 : 5 : 55 is for alpha-particle intensities. Changing it to disintegration intensities, we get 1 : 10 : 55 at 0.8-Mev a.c. for a thick lithium target. In Table III are given comparisons with other data on the ratio $Li^6(d,\alpha)\alpha$: $Li^7(d,\alpha)He^5$: $Li^7(d,\alpha)\alpha,\ n+Li^7(d,\alpha)He^5$ for a lithium target.

The ratio in which we are interested is

$$\frac{Li^7(d,\alpha)\ He^5}{Li^7(d,\alpha)\ He^5+Li^7(d,\alpha)\alpha n}=\frac{10}{55}=\frac{10}{10+45},$$

since it gives the ratio we are seeking,

$$\frac{Li^7(d,\alpha)He^5}{Li^7(d,\alpha)\alpha n}=\frac{1}{4.5}=\frac{He^5(\ ,n)\alpha}{Li^7(d,n)\alpha\alpha}.$$

Hence[19]

$$\frac{He^5(\ ,n)}{Li(d,n)}=\frac{He^5(\ ,n)\alpha}{Li^7(d,n)Be^8+He^5(\ ,n)\alpha+Li^6(d,n)}=\text{about } \tfrac{1}{6}.$$

Hence the neutrons from the breakup of He^5 should be about $\frac{1}{6}$ of the total number of neutrons from lithium bombarded with deuterons.

DISCUSSION

The neutron spectrum shown in Fig. 1 can be interpreted as follows: The high energy group

[19] About 8 percent of the total neutrons are from Li^6 according to reference 5.

TABLE II. *Alpha-particle intensities and ranges.*

Reaction	Intensity (Relative) Differential	Integral	Av.	Ranges in cm Obs.	Calc.
$Li^6(d,\alpha\alpha)$	11.1	12	1	12.95	12.85
$Li^7(d,\alpha)He^5$	47 to 56	44	5	7.3 to 7.6	7.68
$Li^7(d,\alpha\alpha)+He^5(\alpha)n$	537 to 546	414	50	Max. 7.7 to 8.1	8.10
$Li^7(p,\alpha\alpha)$				8.70	8.68
$Li^7(d,\alpha\alpha)+He^5(\ ,\alpha)n+Li^7(d,\alpha)He^5$			55		

TABLE III. *Values for the ratio of disintegration intensities* $Li^6(d,\alpha)\alpha : Li^7(d,\alpha)He^5 : Li^7(d,\alpha)\alpha,\ n+Li^7(d,\alpha)He^5$ *for a lithium target.*

REFERENCE	RATIO	ENERGY	TARGET
Oliphant, Kinsey and Rutherford[1]	1 :— : 10	0.2 Mev d.c.	Thick
Williams, Shepherd and Haxby[2] taken from published curve	1 : 2 : 8	0.2 Mev d.c.	Thick
Published ratio	2 : 3 : 400		
Rumbaugh, Roberts and Hafstad[3]	1 :— : 15	0.2 Mev d.c.	Thin
	1 :— : 100	0.8 Mev d.c.	Thin
Staub and Stephens[4]	1 : 10 : 55	0.8 Mev a.c.	Thick

[1] Oliphant, Kinsey and Rutherford, Proc. Roy. Soc. **141**, 722 (1933).
[2] Williams, Shepherd and Haxby, Phys. Rev. **52**, 390 (1937).
[3] Rumbaugh, Roberts and Hafstad, Phys. Rev. **54**, 657 (1938).
[4] This ratio neglects the contribution of the $Li^6(d,\alpha)He^3$ reaction, and is further uncertain due to the extrapolation to zero energy.

of neutrons is from reaction (2.1). While most evidence[4] indicates that the lowest state in Be^8 is slightly unstable, some recent work has suggested that it is 0.3 Mev unstable.[20] The wider group at 10.5 Mev is from reaction (2.2).[4] Since evidence[5] has been found for

$$^{**}Be^8 \rightarrow He^4 + He^4 + 10 \text{ Mev}, \qquad (2.03)$$

the neutrons around five Mev may be due to reaction (2.3). It would be expected that a ten-Mev level in Be^8 would be wider even than the three-Mev level (which is about one Mev wide). This widening of the levels may account for the overlapping of the neutron groups.

The point at 5.5 Mev obtained with helium recoils is the only point where the helium and hydrogen recoils disagree. Whether this is due to statistical or observational errors or is some departure from the assumed smoothly varying neutron scattering cross section is not known. The curve was drawn through the hydrogen recoil points because the hydrogen cross section is considered more reliably smooth. The helium recoil points above eight Mev were not checked by hydrogen recoils because of the difficulty of getting pressures high enough to make the hydrogen recoils short enough for accuracy. Hence the high energy part of the curve is still uncertain because of the lack of knowledge of the neutron-helium forward scattering cross section. The only available evidence concerning this comes from comparing the neutron spectrum of boron bombarded by deuterons as measured in helium and methane.[21] This comparison is subject to large error because the high energy hydrogen recoils were slowed down in mica and the geometrical correction for this is large and uncertain. It is further not known whether He^5 has higher levels which would give resonance neutron scattering in helium. It is reasonable however, to assume that higher levels of He^5 would be quite broad and not give spurious neutron groups.

In a two-stage reaction

$$M_0 + M_1 \rightarrow M_3 + M_2 + Q_1,$$
$$M_3 \rightarrow M_5 + M_4 + Q_2,$$

the intermediate nucleus M_3 can come off at almost any angle and still disintegrate to emit a particle M_4 at 90° to the incident particle M_1. Since the energy of recoil depends on the angles, the emitted particle (at 90°) has a spread in energy and this spread can be calculated by the formula:[22]

$$E_4 \gtrless [(Q_2M_2M_4/M + M_0M_2M_4E_1/M^2)^{\frac{1}{2}} \pm (Q_2M_5)^{\frac{1}{2}}]^2/M_3 - M_4M_1E_1/M^2.$$

In this case, using $Q_2 = 0.8$ Mev, $E_1 = 0.8$ Mev and $Q_1 = 14.3$ Mev for the reactions (1) and (1.0), we get 0.1 Mev$<E_4<$3.8 Mev. Hence the neutrons would be expected to have a spread in energy from 0.1 Mev to 3.8 Mev. Therefore the sharp rise in number of neutrons at 3.8 Mev in Fig. 1 is interpreted as the high energy end of the neutron continuum from reaction (1.0). Making reasonable guesses as to the distribution of these neutrons, we estimate them to be $\frac{1}{5}$ to $\frac{1}{6}$ of the total number of neutrons, in excellent agreement with the ratio calculated from the alpha-particle

[20] Allison, Graves, Skaggs and Smith, Bull. Am. Phys. Soc. **13**, 14 (1938).
[21] T. W. Bonner and W. M. Brubaker, Phys. Rev. **50**, 308 (1936); H. Staub and W. E. Stephens, Phys. Rev. **53**, 212 (1938). Also reference 14.
[22] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 280 (1937).

intensities. This estimate depends on the $(\sigma_{He}/\sigma_H)_{back}$ ratio which is, as we have said, not very well known at energies greater than six Mev. Also the background of neutrons from other modes of disintegration is not well known. Hence the agreement is only valid in order of magnitude, but to this extent supports our interpretation.

These experiments indicate that present data may be explained on the assumption that two-stage reactions are much more probable than three-particle reactions. However, they do not give a decisive answer as to whether three-particle reactions occur with any measurable probability or not. The relative probabilities of a three-particle reaction compared to a two-stage reaction might be gotten by accurately measuring the neutron spectrum of separated Li^6 bombarded by deuterons.[23] If the reaction goes in two stages

$$Li^6+D^2\rightarrow He^5+He^3+0.8\text{ Mev}, \qquad (4)$$

$$He^5\rightarrow He^4+n^1+0.8\text{ Mev}, \qquad (4.0)$$

the neutrons will have a spread in energy from 0.18 Mev to 1.22 Mev (for 0.8 Mev bombarding energy) while if the three-particle reaction occurs

$$Li^6+D^2\rightarrow He^4+He^3+n^1+1.6\text{ Mev}, \qquad (5)$$

the neutrons will have energies from 0 to 1.85 Mev. In addition, the maximum energy of the neutrons will vary much faster with bombarding energy in the case of the three-particle reaction than the two-stage reaction.

We wish to thank Mr. Tom Lauritsen for the electroscope, the Seeley W. Mudd Fund for financial support, and Dr. C. C. Lauritsen for continued encouragement. One of us (H. Staub) is very much indebted to the "Stipendienfond" and the "Jubilaumsfond der Eidgenossischen Technischen Hochschule" Zurich, Switzerland for a grant.

[23] Rumbaugh, Roberts and Hafstad, reference 5, have measured this neutron spectrum, but not accurately enough for this purpose.

MAY 1, 1939 PHYSICAL REVIEW VOLUME 55

The Magnetic Rotation Spectra of SO_2 and CS_2 in the Ultraviolet

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(Received March 15, 1939)

The apparatus previously used for the study of magnetic rotation spectra in the visible and infra-red has been modified for use in the ultraviolet. The object was to see whether the simplification often found in magnetic rotation spectra will help in the analysis of the complicated spectra associated with electronic transitions of polyatomic molecules, most of which occur in the ultraviolet. The spectra of this type which have been found are those of CS_2, SO_2 and formaldehyde. In each case the band spectrum is replaced by sharp lines which may readily be correlated to band heads. These spectra occur for only limited regions of the absorption spectrum, in which the band heads are rather sharp and present a regular appearance. In the region where the band heads are irregular and confused in appearance, no effect occurs. In no case is the magnetic rotation spectrum sufficiently extensive to permit a vibrational analysis of the band system to be made, nor to give any material aid in its analysis.

INTRODUCTION

THE magnetic rotation spectrum of a gas is the spectrum of light transmitted by a gas between crossed polarizing prisms when the gas is placed in a magnetic field parallel to the direction of propagation of the light beam. Several types of magnetic rotation spectra have been observed. The most usual type occurs in the region of the $^1\Pi\leftarrow{}^1\Sigma$ absorption systems of the alkali metal molecules and consists of a number of fairly sharp lines which lie near the band heads of the corresponding absorption system. These magnetic rotation spectra have been observed[1] for all

* Now at Columbia University.

[1] F. W. Loomis and R. E. Nusbaum, Phys. Rev. **38**, 1447 (1931); **39**, 89 (1932); **40**, 380 (1932). F. W. Loomis and M. J. Arvin, Phys. Rev. **46**, 286 (1934). P. Kusch, Phys. Rev. **49**, 218 (1936).