Energy Levels in Sulfur Nuclei*

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A study has been made of the proton groups from the reaction of 3.22-Mev deuterons with sulfur in the form, primarily, of H_2S gas. The following Q values have been assigned to the reaction $S^{32}(dp)S^{33}$: 6.48, 5.69, 4.58, 4.31, 3.63, 3.33, 2.60, 2.33, 2.06, 1.78, 1.37, 0.85, and 0.18 Mev, corresponding to the ground state and twelve excited states of S^{33}. Four of these groups have been investigated for proton gamma-ray coincidences to confirm this assignment. The yield as a function of deuteron energy has been observed for the six highest energy groups and indication of the presence of some broad resonances found. A qualitative measurement of the variation with angle of relative yields of the groups has indicated a proton intensity distribution that is symmetric for some groups and asymmetric for others. The cross section for the reaction for 90° observation has been found to be 1.2 barns. The mass difference $S^{33}-S^{32}$ has been calculated to be 0.99963 mass unit.

Two low intensity, high energy groups have been assigned to the reaction $S^{33}(dp)S^{34}$ with Q values of 8.67 and 7.85 Mev. This, together with the above observation, leads to a value of 1.99691 for the mass difference $S^{34}-S^{32}$.

INTRODUCTION

THE existence of nuclear energy levels has been known for approximately twenty years during which period a considerable amount of information on them has been compiled.[1-3] The accumulation of evidence has been going forward in several laboratories, and in recent years the use of improved counting and bombardment techniques has enabled the extension of accurately known energy levels and mass values as far as Ne^{22}. Only a moderate amount of information is available beyond this element.

The element selected for the present investigation was sulfur which normally consists of four isotopes: S^{32}, 95.1 percent; S^{33}, 0.74 percent; S^{34}, 4.2 percent; and S^{36}, 0.016 percent. Of the several methods available for studying nuclear energy levels, the one chosen here involves the observation of proton groups from transmutations induced by deuteron bombardment. A preliminary study of this element was reported by Smith and Pollard,[4] who found six groups with an average spacing of 0.9 Mev.

Thin targets of solid sulfur are difficult to use inasmuch as this substance readily sublimes. However, gaseous H_2S is available in 99.9 percent pure form, and it was decided to use this as the target material.

EXPERIMENTAL APPARATUS

The bombardment chamber used in most of this work was one especially designed for gaseous targets. Aside from the fact that certain elements, e.g., neon and argon, can be obtained only in gaseous form, this type of target has distinct advantages to recommend it; uniform targets of any desired degree of thinness may be prepared and duplicated with ease and accuracy. This is of particular importance if the substance under study dissociates under bombardment, as does H_2S.

This bombardment chamber, illustrated in Fig. 1, consists of two sections: a chamber to

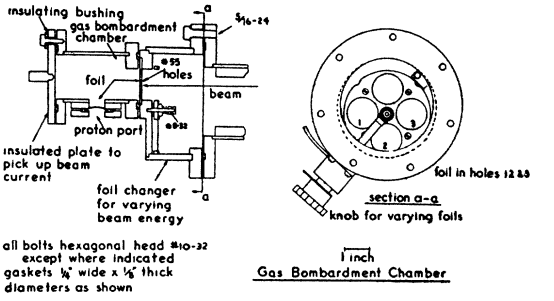

FIG. 1. A drawing showing the construction of a chamber for bombardment of gaseous targets with deuterons or alpha-particles from the Yale University cyclotron. This chamber includes a foil changer in the path of the beam for altering the bombarding beam energy.

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[1] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 245 (1937).
[2] W. F. Hornyak and T. Lauritsen, Rev. Mod. Phys. 20, 191 (1948).
[3] Ernest Pollard, Nucleonics 2, No. 4, 1 (1948).
[4] E. Smith and E. Pollard, Phys. Rev. 59, 942A (1941).

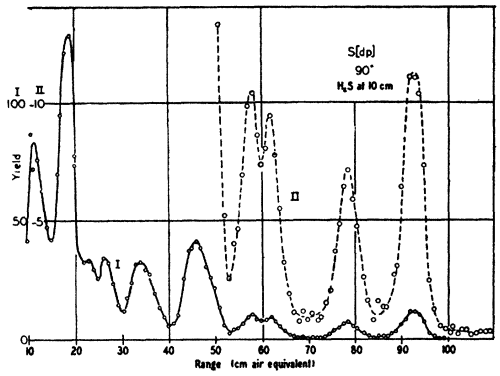

FIG. 2. The proton group spectrum for 90° observation of the reaction $S(dp)$. An H_2S target at a pressure of 10 cm Hg was used. All the groups shown have been assigned to the reaction $S^{32}(dp)S^{33}$.

contain the gas and a foil changer to alter the deuteron beam energy. The gas chamber is isolated from the cyclotron proper by means of an aluminum foil. In order to minimize the reduction in beam energy, the foil used is quite thin, approximately 2 cm of air equivalence, and cannot withstand the force due to the difference in pressure between the chamber and the cyclotron. For this reason the foil is supported on the vacuum side by a grid formed by drilling No. 55 holes in a brass plate. The protons produced in the nuclear reaction under study are observed through a "proton port" sealed by an aluminum foil. For most purposes a foil of sufficient thickness, 3 cm air equivalence or greater, may be used, and hence it need not be supported. However, for the use of thinner foils a holder has been constructed with grids on both sides of the foil. The arrangement of the foil changer is clear from the figure. The foil in the beam, and hence the beam energy reduction, may be selected, without breaking the vacuum, by means of the knob on a shaft through a Wilson seal. The foil selected is locked in position by means of a spring-operated catch on the rim of the foil changer wheel.

The bombardment chamber used for 0° observations and for proton gamma-ray coincidence measurements was constructed by Dr. Benson. It, together with the associated equipment and techniques, have been described by him elsewhere.[5] The solid target required by this bombardment chamber was prepared in the following manner. A thin layer of sulfur was deposited by evaporation on a clean gold foil. On top of this a thin layer of gold was deposited in a similar manner. The purpose of this gold coating was to inhibit the sublimation of the sulfur target. It was found that an uncoated sulfur target of 1 mg/cm² completely disappeared when in a vacuum for a period of several hours. A rough calculation using the vapor pressure of sulfur showed that this is as expected. Therefore, it was impossible to determine accurately the thickness of either the sulfur target or the gold coating, inasmuch as sulfur was lost in the process of applying the gold.

The absorption method was used to determine the proton energies. In this conjunction a mechanical foil changer was used. This instrument could be operated by remote control from the cyclotron control room and the absorption in the path of the protons could be varied in 1-cm steps to a total of 164 cm. When it was desired

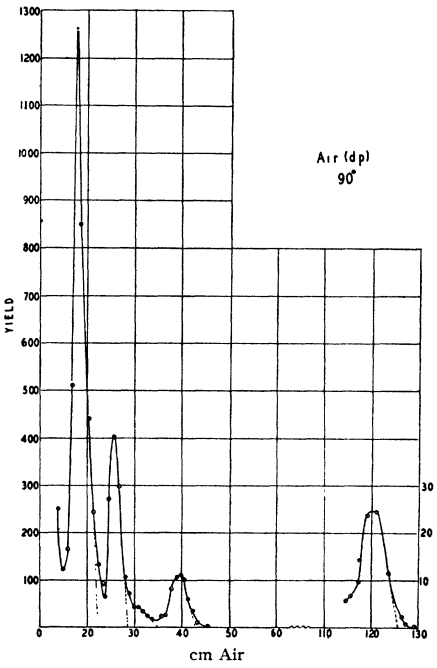

FIG. 3. The proton group spectrum for 90° observation of the reaction of deuterons with air at a pressure of 10 cm Hg. This information was obtained because of the possibility of air contamination in H_2S. The two longest range groups are due to nitrogen. The 25-cm group is due to oxygen. The 20-cm group is a composite of nitrogen and oxygen groups.

[5] B. B. Benson, Rev. Sci. Inst. **17**, 533 (1946) and Phys. Rev. **73**, 7 (1948).

to obtain increments in range of less than 1 cm, a gas absorption cell was used.

Proportional counters were used for proton detection. These were constructed under the direction of Dr. Martin.[6] The short recovery time of this type of counter allows it to be used at high counting rates. When the proper preamplifier is used, the counter pulse shape is quite good—0.1 μsec. rise time and 1.0 μsec. width, and hence short resolving-time (2×10^{-7} sec.) coincidence measurements may be made. Furthermore, the pulse amplitudes are proportional to the initial ionization produced by the particle passing through the counter. Thus, by setting the level in the counting circuits such that only pulses with an amplitude greater than a certain fixed value are recorded, one may make use of the peak in the Bragg ionization curve to restrict observations to only a small interval of range. This process is known as "peaking."

The associated electronic circuits consisted of capacity-neutralized preamplifiers, wide band (4 mc/sec.), video amplifiers, and a variable resolving time coincidence circuit. These were designed by Professor H. A. Schultz and are described elsewhere.[5-7] In addition, a modified Higinbotham scale-of-64 circuit was used when the counting rate required it.

EXPERIMENTAL RESULTS

The proton group structure as observed at $90°\pm5°$ is shown in Fig. 2. In this figure the yield, counts per minute per unit beam current, is plotted as a function of the absorption, in cm air equivalence, in the path of the protons. There are ten groups of protons which are clearly resolved. The two groups in the neighborhood of 35 and 50 cm have half-widths larger than those of longer range. This would lead one to expect that they are multiple.

IMPURITIES

As mentioned above, the H_2S used was 99.9 percent pure, the 0.1 percent impurity being due to hydrogen, water, and traces of BaCl and NaCl.[8] The hydrogen and barium would not be expected to cause complications. The reactions with Na and Cl give groups lying within the sulfur spectrum.[9,10] On the other hand, their concentrations are at most a fraction of 0.1 percent and certainly would not be responsible for groups of the intensities found. The oxygen in water was considered along with that in air, which had to be taken into account since the manometer system used to introduce the H_2S into the bombardment chamber could not be completely freed of leaks and occluded air. For this reason information on the proton groups due to air was obtained. The results are shown in Fig. 3. It will be noted that there are groups in the neighborhood of 20, 25, 40, and 120 cm. The two groups at 20 and 25 cm coincide almost exactly with groups in the sulfur spectrum. These two groups would be expected to have different excitation functions, i.e., variations of yield with beam energy, depending on whether they are due to sulfur or air. This portion of the spectrum of the two substances is shown in Fig. 4 for two different beam energies. It is clear that the yield of the longer range sulfur group increases relative to the shorter range one for a decrease in beam energy, while for air just the reverse occurs. Furthermore, it was observed that in order to account for the intensities of the H_2S groups air would have to be present to the extent of 50 percent, which was certainly not

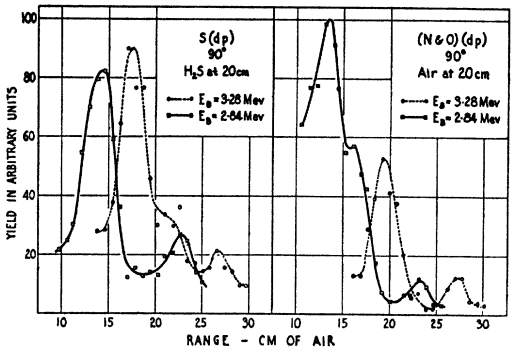

FIG. 4. The 20- and 25-cm groups from the bombardment of H_2S and air targets with deuterons of two different energies. The variation of relative intensity of the two groups with bombarding energy is not the same for the two targets. For this reason, it is concluded that the two groups from the H_2S target are not due to the presence of air.

[6] A. B. Martin, Phys. Rev. **72**, 378 (1947).
[7] H. A. Schultz and R. Beringer, Rev. Sci. Inst. **19**, 424 (1948).
[8] Matheson Company, Inc., East Rutherford, New Jersey, private communication.
[9] E. B. M. Murrell and C. L. Smith, Proc. Roy. Soc. **173**, 410 (1939).
[10] E. F. Shrader and E. Pollard, Phys. Rev. **59**, 277 (1941).

the case. From this combined evidence it is concluded that the two groups in question are due to sulfur.

A low intensity group, not shown in Fig. 2, was noted at 120 cm. However, its intensity was so low, about two percent of that of the 100-cm group, that no quantitative measurements could be made. It was observed that this group's intensity was roughly independent of H_2S pressure. This, in addition to the range, leads one to believe that the group is due to nitrogen from air. Even though this be the case, no complications would be expected from the 40-cm nitrogen group inasmuch as the H_2S groups in this region are considerably more intense than that group would be.

RESOLUTION OF MULTIPLETS

As mentioned above, the half-widths of two of the groups indicate that they may be unresolved multiplets. There are several factors that enter into the resolving power of this method; beam homogeneity, target thickness, range and angle straggling, and degree of peaking. An attempt was made to improve the largest factor, beam homogeneity, by using a system of three slits in conjunction with the field of the beam analyzer magnet. A noticeable improvement, reduction of beam half-width from 0.18 to 0.08 Mev, was obtained but with such a loss in beam intensity that satisfactory data could not be taken. The target thickness for H_2S at 10 cm pressure was 3 mm or 0.05 Mev. Range straggling is inherent in the absorption method of measuring energy and hence would not be circumvented. It amounts to 1.9 percent of the range or about 0.06 Mev at 50 cm. The angle straggling can be lessened by improving the geometry of the detection. The effect of "peaking" can be elimi-

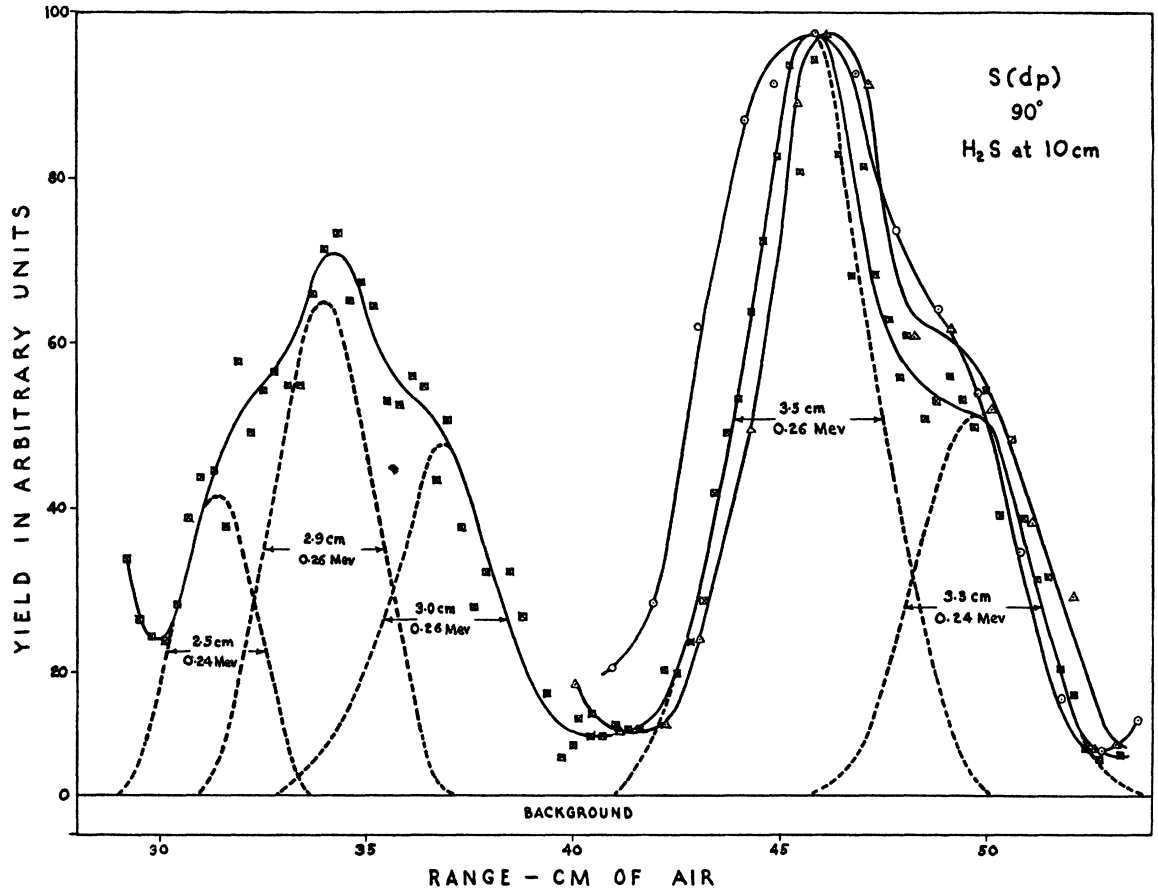

FIG. 5. The resolution of the 35- and 50-cm groups in the H_2S spectrum into their components. The 50-cm doublet is shown for three different conditions of peaking and geometry. The dotted curves were obtained graphically.

nated by setting the level at such a value that further increase causes no decrease in half-width of the group. Figure 5 shows the 50-cm multiplet for three conditions of peaking and geometry. The scatter of the observed points is explicable in terms of statistical fluctuations. The dashed curve shows the resolution into two groups. This was done in the following manner; the long-range edge of the group was reflected graphically about a vertical line, so chosen as to give the expected half-width for the resulting curve. The curve so obtained was subtracted from the observed curve to give the long-range side of the shorter range group. It will be noticed that the resulting half-widths are almost identical. Observations under the same conditions as above failed to give any clear-cut resolution of the 35-cm group into its components. There was some indication for three groups, and a graphical analysis such as just described was made and is also shown in Fig. 5. However, the identification of these three groups is not considered to be as positive as that of the two 50-cm groups.

ASSIGNMENT TO ISOTOPES

In order to check the possibility that the abrupt changes in yield at the 50-cm group (see Fig. 2) could be explained on the basis of the isotope configuration, a proton gamma-ray coincidence study was made. This technique allows the location of groups corresponding to ground states, inasmuch as no gamma-rays should be associated with such groups. The results obtained are given in Table I and in Fig. 6. In the latter is shown the group structure as observed at 0° and with large solid angle proton detection. The number of coincidences per 10^4 protons is given at the peak of the group concerned. The expected number of random coincidences, as determined from the relation $2\tau N_p N_\gamma = N_r$, has been subtracted from the number of observed coincidences. This method of determining the number of random coincidences was not precise, inasmuch as neither the resolving time τ nor the number of gamma-rays N_γ was very well known. τ was determined by placing a beta-ray source between two counters and observing the number of coincidences detected. The relation given above was then used and the value of τ obtained was 2×10^{-7} for the setting of the resolving time dial used in the above. N_γ was determined by means of a counting rate meter calibrated in the region used with a scaling circuit. These two factors undoubtedly account for the fact that there are residual coincidences associated with the longest range group. However, the object of prime interest was the first high intensity group and the results obtained showed that at least the prominent member of this group does not correspond to a ground state. Because of the large solid angle required, it was impossible to resolve either this group or the next longer range group into its components, and hence this method of attack was abandoned. Before leaving this subject, it might be remarked that the number of gamma-rays associated with the individual groups seems to be roughly proportional to the yield of the group. This would indicate that gamma-ray transitions in the residual nucleus are more frequently to the ground state than to intermediate states. However, it is difficult to conclude anything quantitative from these observations for the following reasons: the efficiency of the gamma-ray counter is energy dependent, the gamma-ray intensity is not likely to be spherically symmetric, and, furthermore, the

TABLE I. $S(dp)$, 0°, $P-\gamma$-coincidences.

Q* Mev	N_p Total	$N\gamma$ per sec.	T per min.	N_c Total	N_c per 10^4 protons	N_r per 10^4 protons	N_c per 10^4 protons corrected
6.48	40,000	384	83	9	2.25±0.9	1.54	0.71
	80,000	435	153.5	23	2.88±0.6	1.74	1.14
5.69	80,000	410	84.5	51	6.38±0.9	1.64	4.74
3.33	80,000	384	25.5	77	9.63±1.1	1.54	8.09
2.60	80,000	349	51.5	71	8.88±1.1	1.39	7.49

* From analysis of 90° data.

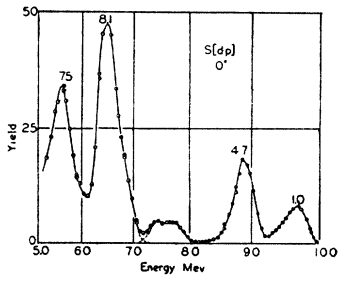

FIG. 6. The $S(dp)$ spectrum for 0° observation. The numbers at the peaks of the various proton groups give the number of proton γ-ray coincidences observed per 10^4 protons counted from that group.

TABLE II. $S^{32}(dp)S^{33}$.

Q Mev	Level Mev	Relative intensity	Level spacing Mev
6.48	0	1	
5.69	0.79	0.5	0.79
4.58	1.90	1	1.11
4.31	2.17	1.5	0.27
3.63	2.85	5	0.68
3.33	3.15	8	0.30
2.60	3.88	4	0.73
2.33	4.15	6	0.27
2.06	4.42	4	0.27
1.78	4.70	4	0.28
1.37	5.11	5	0.41
0.85	5.63	15	0.52
0.18	6.30	8	0.67

two shortest range groups studied are unresolved multiplets.

In the process of the investigation just described, it was noted that there was a small yield of protons even beyond the longest range group shown in Fig. 6. The results of a more detailed study of this region of the spectrum are given in Fig. 7. The left curve was taken with a thick solid target and shows the presence of a group ending at 148 cm. Observations were made on out to an absorption of 195 cm with no indication of further groups. The right curve given in Fig. 7 was obtained with a thin target, less than 1 mg/cm², and with moderately good geometry and peaking. There is definite indication of group structure. However, the analysis into two groups as shown cannot be considered as very reliable, inasmuch as the background count is of the same order of magnitude as that due to the groups. The longest range group has a range in the neighborhood of that that would

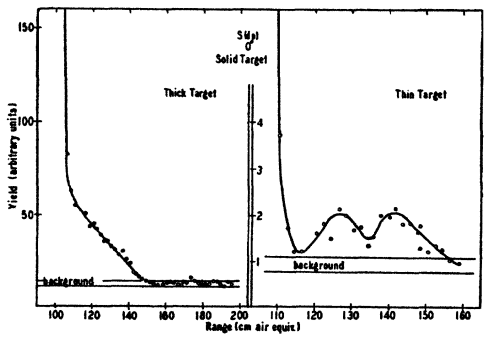

FIG. 7. Long-range, low intensity proton groups observed at 0° with thick (left curve) and thin (right curve) solid sulfur targets. The two groups observed have been assigned to the reaction $S^{33}(dp)S^{34}$.

be expected for the ground state group of nitrogen. Yet it seems unlikely that there could have been enough occluded nitrogen to account for even the low yield observed. On the basis of yield, about one percent of the longest range group in Fig. 6, and the Q value expected from existing mass values, it has been concluded that these two groups are due to the reaction $S^{33}(dp)S^{34}$.

The mass values available for S^{34} and S^{35} indicate that the ground state group from the reaction $S^{34}(dp)S^{35}$ would have a range of 67 cm for 90° observation. This is almost precisely the observed range of the long-range member of the first doublet. For this reason one is tempted to assume that the multiplet structure in the sulfur spectrum is due to the overlapping of the S^{33} and S^{35} spectra. It is regrettable that proton gamma-ray coincidence measurements could not be made on this doublet. However, the intensities of the members of each multiplet are very nearly the same, whereas the concentration of S^{32} is 23 times that of S^{34} which would require that the cross section for the $S^{34}(dp)S^{35}$ reaction be about 20 times that of the $S^{32}(dp)S^{33}$ reaction. While this is not out of the realm of possibility, it does seem unlikely. Therefore, on the basis of the existing evidence it appears that one must conclude that all except the two long-range low intensity groups (Fig. 7) are due to the reaction $S^{32}(dp)S^{33}$. This matter will have to await definite settlement until separated isotopes are available.

Q VALUES

The Q, energy change, values of the reactions may be calculated from the Q equation:

$$Q=[(M_n+M_p)/M_n]E_p-[(M_n-M_B)/M_n]E_B - 2[(M_pM_BE_pE_B)^{\frac{1}{2}}/M_n]\cos\theta,$$

obtained by applying conservation of energy and momentum to the reaction. The masses M_n, M_p, and M_B of the nucleus formed, the proton and the deuteron and the angle of observation, θ, relative to the direction of the beam, are all known. It remains to determine the beam energy, E_B, and the proton energies, E_p. The mean beam energy was found by Martin[5] to be 3.68 ± 0.05 Mev with a half-width of 0.18 ± 0.05 Mev. Recent observations by Pollard, Sailor,

and Wyly agree with these values. The value of the beam energy that must be used for the observations with gas targets must be reduced (average value used was 3.22 Mev) due to the presence of the aluminum foil and 4.22 cm of gas in the path of the beam. The latter correction involves the stopping power of H_2S, which was obtained in the following manner. It was observed that after a long run the position and amplitude of the 100-cm group were changed relative to their values at the start. The group moved out in range and down in amplitude. Both of these effects are readily explained in terms of loss of sulfur from the target due to dissociation of the H_2S by the deuteron beam. This loss was confirmed by the appearance of solid sulfur in the bottom of the bombardment chamber. The increase in range observed is due to two processes: increase in beam energy and decrease of absorption of the three cm of gas in the proton path, both of which are caused by the decreased stopping power of the gas. The effective stopping power, S, at any time can be expressed by the relation

$$(\text{fraction of } H_2S)\times S_{H_2S} + (\text{fraction of } H_2)\times S_{H_2} = S.$$

The fraction of H_2S at the end of the run can be obtained from the yield relative to that at the start of the run and the stopping power of H_2 is known to be 0.22.[11] A plot of change in range *vs.* stopping power of H_2S was calculated for an observed change in sulfur content of 75 percent. From the observed change in range, 3.5 cm for gas at a pressure of 20 cm, it was concluded that the stopping power of H_2S is 1.3 relative to air. Strictly speaking, this is a composite stopping power inasmuch as the actual stopping power is a function of the velocity of the particle and thus is different for the 10-cm deuterons and 100-cm protons. This value was used for all proton groups. However, the error thus introduced is quite small, being only 0.02 Mev for the shortest range group for a change in stopping power of 30 percent.

The values of the mean proton energies corresponding to the various groups were calculated according to the method outlined by Livingston and Bethe[1] in which corrections are made for the variation of aluminum stopping power with range, and for range and angle straggling. Refinements of this method are being worked out by Humphreys and Motz[12] in order that corrections for beam inhomogeneity and peaking level may be made. The Q values obtained are given in Table II, together with the proposed energy level scheme, the relative intensities of the levels, and the separation of the levels. In determining the relative intensities, account had to be taken of the loss of sulfur during the period of observation. Figure 8 shows the relation obtained for H_2S remaining *vs.* amount of bombardment in microampere minutes. This curve was obtained by observing the decrease in amplitude of the 100-cm proton group after a known amount of bombardment. Part of the scatter of the points is due to statistical fluctuations, which are indicated as errors. The effect of changes in counting level could not be assessed, but every attempt was made to minimize it. These data also allow

TABLE III. $S^{33}(dp)S^{34}$.

Q Mev	Level Mev	Relative intensity	Level spacing
8.67	0	1	0.82
7.85	0.82	1	

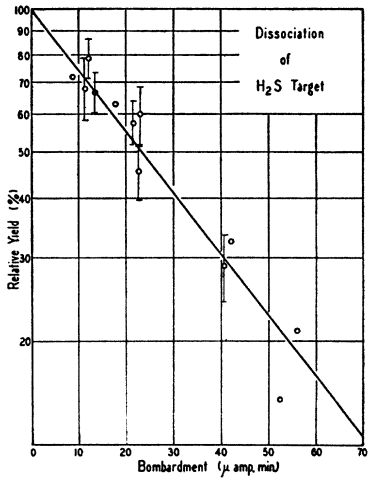

FIG. 8. A curve showing the rate of dissociation of H_2S by 3.2-Mev deuterons. This curve was used to calculate a cross section for dissociation of H_2S and to correct proton group intensities.

[11] See reference 1, p. 272.

[12] R. F. Humphreys and H. T. Motz, Phys. Rev. **74**, 1232(A) (1948).

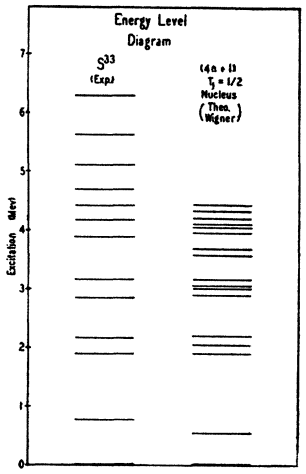

FIG. 9. Energy level diagrams comparing the experimental results given in Table II with the theoretical results obtained by Wigner. The energy scale of the theoretical diagram has been adjusted so that the ground states and second excited states agree in the two cases.

a calculation of the cross section for dissociation of H_2S by 3.2-Mev deuterons. The value obtained is

$$\sigma_{diss}=4.8\times10^{-16}\ \text{cm}^2.$$

It is difficult to assign an error to this figure because, in addition to the errors in the observations, there are errors in the cross-sectional area and uniformity of the beam.

The Q values for the $S^{33}(dp)S^{34}$ reaction were calculated indirectly, inasmuch as the target thickness was not precisely known. It was assumed that the longest-range high intensity group observed at 0° has a Q of 6.48 Mev. The difference in Q value between this group and the low intensity group in question was calculated using a modification of the Q equation. Then by adding this ΔQ to 6.48 Mev the values given in Table III were obtained. The remarks made above concerning the uncertainty about the excited state must be born in mind in considering this table.

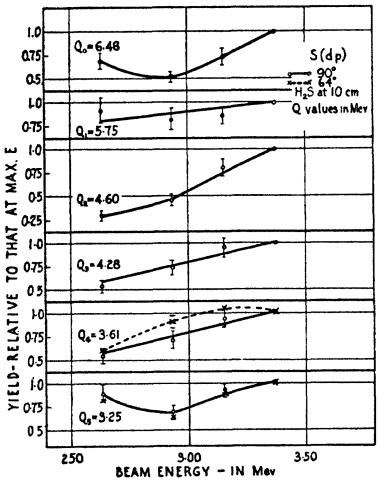

FIG. 10. The excitation functions for the ground state and first five excited states of the reaction $S^{32}(dp)S^{33}$ for 90° observation and the fourth and fifth excited states for 64° observation. The presence of broad resonances is indicated in several instances.

An analysis of the various sources of errors involved in the experimental method together with the repeatability of the data has led to an assignment of a probable error of ±0.11 Mev to the Q values and of ±0.05 Mev to the level spacing for the reaction $S^{32}(dp)S^{33}$. The probable error assigned to the Q values for the reaction $S^{33}(dp)S^{34}$ is ±0.25 Mev.

The energy level scheme based on Table II is given diagrammatically in Fig. 9. Also included in that figure is an energy level diagram obtained from theoretical considerations by Wigner[13] for $4n+1$ nuclei with one more neutron than proton, to which class S^{33} belongs. In the latter diagram the energy scale is not specified and in this figure has been expanded (linearly) to fit the second excited state. Only qualitative comparison can be made with the experimental results, yet there is a striking similarity between the two.

REACTION CROSS SECTION

In order to calculate the cross section of the $S^{32}(dp)S^{33}$ reaction, an integral numbers *vs.* range curve was taken by setting the counting level as low as possible. In this manner was determined the total number of particles corresponding to the end group that were emitted within the solid angle subtended by the counter. Knowing the beam intensity, time of observation, and number of sulfur nuclei in the target volume, one may calculate the cross section for the reaction that leaves the nucleus in the ground state. This was found to be $1.9\times10^{-26}\ \text{cm}^2=1.9\times10^{-2}$ barn. Using the information above on the relative intensities of the various groups, one may calculate the cross sections for the total reaction. It

[13] E. Wigner, Phys. Rev. **51**, 106 (1937).

was noted that for the three longest range groups there is substantial agreement between relative yields as determined from the integral curve and from the peaked curve. Hence, it is perfectly satisfactory—in fact, preferable—to obtain this information from the peaked data. The cross section obtained is

$$(\sigma S^{32}(dp))90° = 1.2 \times 10^{-24} \text{ cm}^2 = 1.2 \text{ barns},$$

which applies to 90° observation only inasmuch as the angular distribution of proton intensities is not spherically symmetric. The error in this figure is probably at least 50 percent and cannot be definitely assigned because many of the errors involved cannot be accurately estimated with the present experimental arrangement.

MASS VALUES

From the ground state Q values obtained above and the mass spectrographically determined masses of H^1 and H^2 (taken from Segrè's table) the following mass differences may be calculated.

$$S^{33} - S^{32} = 0.99963 \pm 0.00012,$$
$$S^{34} - S^{32} = 1.99691 \pm 0.00037.$$

Using the mass spectrographically determined value[14] of the mass of S^{32}, the masses of S^{33} and S^{34} may be obtained. These, together with Okuda's and Ogota's value,[14] are given in Table IV.

From the above mass differences one may calculate the mass difference ratio:

$$(S^{33} - S^{32})/(S^{34} - S^{32}) = 0.50059 \pm 0.00015.$$

TABLE IV. Mass values.

Nucleus	From $S(dp)$	From mass spectrograph[a]
S^{32}	—	31.98089±0.00007
S^{33}	32.98052±0.00020	—
S^{34}	33.97780±0.00044	33.97711±0.00033

[a] See reference 14.

This is in very good agreement with the value of 0.50066±0.00015 obtained by Townes[15] from recent measurements on the microwave spectrum of the molecule OCS.

EXCITATION FUNCTIONS

Using the bombardment chamber foil changer described above, an investigation was made of the variation of the intensity of the six longest range groups of the reaction $S^{32}(dp)S^{33}$ as a function of beam energy. The results obtained are shown in Fig. 10. The beam energies and Q values indicated are extrapolated values. The loss of target due to dissociation has been corrected for by means of the curve in Fig. 8. The errors assigned are based on those expected from statistical fluctuations and do not include the effects of changes in counting level. The latter were minimized by taking the observations in as rapid sequence as possible. Where assigned errors will allow, straight lines have been drawn. The lack of a resonance in the compound nucleus within the range of energies covered would be indicated by a nearly linear excitation function. This appears to be the case for Q_3 and Q_4 and possibly for Q_1. The curves for Q_0 and Q_5 indicate the presence of a resonance slightly below 2.6

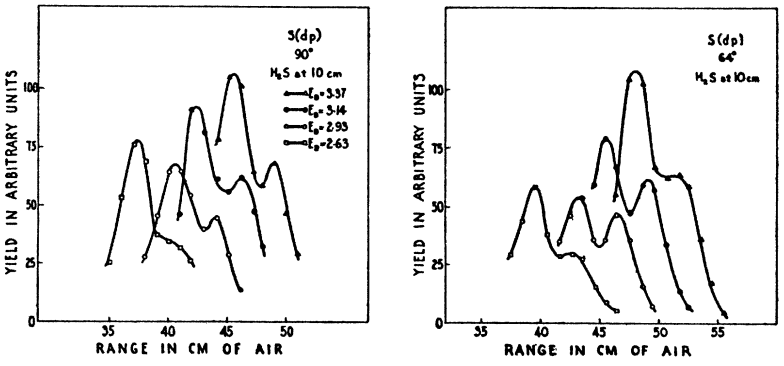

FIG. 11. The 50-cm doublet of the $S^{32}(dp)S^{33}$ reaction as observed for four beam energies and two angles of observation (90° and 64°). These results demonstrate the possibility of resolving a suspected multiplet by the proper choice of bombarding energy and angle of observation.

[14] T. Okuda and K. Ogota, Phys. Rev. 60, 690(L) (1941).
[15] C. H. Townes, private communication, June 22, 1948. C. H. Townes, A. N. Holden, and F. R. Merritt, Phys. Rev. 74, 1113 (1948).

TABLE V. Relative yields at various angles for $S^{33}(dp)S^{34}$.

Level	Yield 90° Relative to Q_0, 90°	64°	0° Relative to Q_0, 0°
Q_0	1	1.5	1
Q_1	0.5	1.2	3
Q_2	1	1	0.5
Q_3	1.5	1.5	0.5
Q_4	5	6	2
Q_5	8	9	6
Q_6	4	—	—
Q_7	6	6	4
Q_8	4	—	—
Q_9	4	5	5
Q_{10}	5	7	—
Q_{11}	15	18	15

Mev. That for Q_2 indicates the presence of a resonance above 3.4 Mev. The resonances for the various groups would not be expected to fall at the same place inasmuch as their location is dependent on the angular momentum quantum numbers of the particles involved. These resonances are expected to be broad inasmuch as the levels in the compound nucleus are believed quite closely spaced and the beam energy is not sharply defined.

Figure 10 also gives the results of a similar study for Q_4 and Q_5 at 64° observation. The curve for Q_5 is essentially identical with that obtained at 90°. However, for Q_4 the observations at 2.93 Mev differ by more than the assigned errors and the curve for 64° indicates a resonance in the neighborhood of 3.2 Mev. There is some indication of such a resonance in the 90° data but not to the same degree.

In the process of these investigations the curves shown in Fig. 11 were obtained for the 50-cm doublet. They show how the resolution of a suspected multiplet into its various components might be facilitated by the proper choice of beam energy and angle of observation. At 2.63 Mev and 90° the long-range member has been suppressed, where as at 2.93 and 64° the two components are almost equal in amplitude. This effect was also observed in conjunction with the 20-cm group in air (Fig. 4) which is composed of overlapping oxygen and nitrogen groups. This method requires, however, that the excitation functions for the components be markedly different which, in general, may not be the case.

ANGULAR VARIATIONS

As mentioned above, the intensity of a proton group is dependent on the angle of observation. This dependence is related to the angular momentum quantum numbers of the particles involved in the reaction. This effect has been studied in considerable detail for several reactions.[16] With the present equipment it was not possible to make a detailed study for this reaction. Nevertheless, observations were made at 90°, 64°, and 0°, and their results are shown in Table V. The 90° and 64° data were taken with the gas bombardment chamber, and hence it was possible to correlate the two by taking into consideration the geometrical differences involved. The 0° information was obtained with a solid target whose thickness could not be precisely determined. The results given in Table IV seem to indicate the following about the symmetry of the proton intensity patterns. Those resulting from Q_0 and Q_1 are definitely asymmetric; those from Q_2 and Q_3 are symmetric; those caused by the remaining groups are somewhat asymmetric.

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[16] E.g., N. P. Heydenburg and D. R. Inglis, Phys. Rev. 73, 230 (1948).