this is much higher than the 1.4 percent found in the center and supports the view that the reaction is exothermic. (The presence of P^{32} shows that a fast neutron flux is still present, of order 10^8 neutrons/cm^2 sec.) The specific activity calculated for sulfur is 0.1 μC/gram, giving a thermal cross section of only 2.3×10^{-3} barn for the $S^{33}(n,p)P^{33}$ reaction. This is about 7 percent of the cross section found for the neutrons in the center. It seems safe to assume that the fast neutron flux might be simply reduced by at least a factor of ten by means of moderating material, thus directly making P^{33} at least 90 percent pure. It is possible, moreover, to use a much higher neutron flux (e.g., in Chalk River), where the order of one millicurie P^{33} per kg sulfur might be produced.

The chemical identity proof for P^{33} involved dissolving of the sulfur in CS_2, filtering through a pile of filter papers (more than 60 percent of the P-activity was found on the first paper, whereas S^{35} went through), treating the paper with HNO_3 and a 0.1-mg phosphate carrier, lanthanum precipitation,[4] dissolving and cation-exchange processing,[4] and finally a molybdate precipitation. Absorption curves for samples from the filter paper, lanthanum precipitation, and the molybdate all showed the same P^{33}/P^{32} ratio within experimental error. The chemical steps should eliminate all cations and most of the anions, except possibly arsenate and silicate. Even if the latter is true, some separation would likely have been observed and, moreover, Si or As isotopes are not likely to be produced from sulfur, for physical reasons.

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Magnetic Analysis of the Proton Groups from the $Na^{23}(d,p)Na^{24}$ Reaction*†

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Thin targets of sodium iodide evaporated onto platinum and thin nickel backings have been bombarded with deuterons accelerated to energies ranging from 1.5 to 2.2 Mev by the large M.I.T. air-insulated electrostatic generator. Proton groups emitted at 90 degrees to the incident deuterons were analyzed with a 180-degree magnetic spectrograph. Twenty of the observed proton groups are assigned to the $Na^{23}(d,p)Na^{24}$, Na^{24*} reaction and correspond with energy levels in Na^{24} up to 4.5 Mev. Several of the groups are closely spaced, and level spacings in Na^{24} as low as 17.0±3 kev have been observed.

I. INTRODUCTION

THE element sodium, atomic number 11, exists in nature as a single isotope of mass number 23. Thus, the protons emitted from the interaction of deuterons on sodium are associated with the formation of Na^{24} in various states of excitation according to the reaction $Na^{23}(d,p)Na^{24}$. Na^{24} subsequently decays with a half-life of 14.9 hours to Mg^{24} by emission of 1.390-Mev beta-particle, accompanied by two cascade gamma-rays of 2.758 and 1.380 Mev.[1]

At the present time, the determination of the lower energy levels in Na^{24} can best be made by either of two methods. The gamma-ray spectra observed from slow neutron capture in Na^{23} can give information regarding radiative transitions between the levels of the residual nucleus, according to the reaction $Na^{23}(n,\gamma)Na^{24}$. Although not uniquely fixing the positions of the excited levels, such gamma-ray measurements do provide confirmatory evidence for levels assigned from other nuclear reactions. Some recent measurements of gamma-transitions in Na^{24} by Kinsey and his collaborators are discussed later in this paper and are compared with the results obtained here. Measurement of the proton energies from the $Na^{23}(d,p)Na^{24}$ reaction, as done in the present work, yields more directly the energy levels of the residual nucleus.

A number of proton groups from the deuteron bombardment of sodium have been reported by other investigators. Lawrence,[2,3] using deuterons of 2.15 Mev, first observed two proton groups with Q-values of 4.92 and 1.72 Mev. Murrell and Smith,[4] using deuterons of 0.85 Mev, found four groups they attributed to $Na^{23}(d,p)Na^{24}$ with Q-values of 4.76, 4.58, 3.50, and 1.38 Mev. Recently, Whitehead and Heydenburg[5] have made a more

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[1] *Nuclear Data*, National Bureau of Standards Circular 499, 19 (1950).
[2] E. O. Lawrence, Phys. Rev. **47**, 17 (1935).
[3] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (19437).
[4] E. B. Murrell and C. L. Smith, Proc. Roy. Soc. (London) **A173**, 410 (1939).
[5] W. D. Whitehead and N. P. Heydenburg, Phys. Rev. **79**, 99 (1950).

exhaustive investigation at deuteron bombarding energies of 2.0, 2.5, and 3.0 Mev. They report ten groups from the $Na^{23}(d,p)$ reaction. The arithmetic average of their Q-values at the three bombarding energies are listed in Table I.

II. EXPERIMENTAL METHOD

The large air-insulated Van de Graaff generator was used for accelerating deuterons up to 2.2 Mev. After magnetic deflection through 90 degrees, the beam was made to enter a gap in a 180-degree magnetic spectrograph and was focused on the target material, placed at 45 degrees to the direction of the incident deuterons and also at 45 degrees to the main gap of the spectrograph. Charged particles emitted at 90 degrees to the incident beam were thus deflected in the annular gap, and those particles with momentum corresponding to 180-degree deflection for a particular field setting were focused on nuclear emulsions (25-micron Eastman NTA plates) which were placed diametrically opposite to the target and at 30 degrees to the plane of the gap. Further details on the general technique, including experimental arrangement, interpretation of the data, corrections of the measurements, and over-all precision, have been discussed in recent publications.[6–8]

The magnetic spectrograph, since it is a momentum analyzer, will focus protons, deuterons, tritons, and alpha-particles of the same momentum at the same point. Distinction between the particles is then made by observing their ranges in the nuclear emulsion. When a thin target supported on a thick backing is bombarded with deuterons, a continuous distribution of deuterons scattered from the backing material is recorded in the emulsion, starting at the high energy side where the magnet field setting corresponds to the $H\rho$ of the deuterons elastically scattered from the target. The density of these tracks in the emulsion is so great as to make difficult the observation of other particles in this momentum range. For detecting protons in this region, we have generally resorted to a technique in which a sheet of aluminum foil is placed directly in front of the emulsions, the foil thickness being sufficient to stop the deuterons but thin enough for protons to penetrate it and enter the emulsion. An alternative technique is to use a sufficiently thin target backing so that the scattered deuterons obscure only a small region of the momentum spectrum. Although both of these methods have been employed in the present investigation, the results reported are based primarily on the measurements made from targets deposited onto thick supports.

A preliminary survey of the proton groups resulting from the $Na^{23}(d,p)Na^{24}$ reaction was made at a deuteron bombarding energy of 1.5 Mev. A rather thick target was made by depositing a drop of NaOH solution on a thick platinum backing. This made possible rapid survey of the approximate energies and relative yields of the various groups. Because of the deliquescent properties of NaOH, no attempt was made to prepare thinner targets of NaOH for the more exhaustive study. Instead, thin targets of approximately 5-kev thickness were prepared by evaporating NaI onto a 0.010-inch platinum sheet. Several targets were prepared at the same time in order to have available equivalent targets for repeated bombardments, thereby making possible yield comparisons among the various groups. It was found that the amount of NaI on the targets decreased during prolonged bombardment. Hence, the region of bombardment on a particular target was changed or a fresh target was used whenever the exposure exceeded a few microampere hours. This procedure also tended to minimize the effects of surface contaminations on the energy measurements, since it is observed that the thickness of surface layers, such as that from carbon, increases with bombardment time. For the observation of the low energy proton groups, targets prepared on 0.1-micron nickel foils[9] were also used in the region of $H\rho$ below 290 kilogauss-centimeters, but the results obtained were unsatisfactory for precision measurements. A broad proton distribution was usually observed even with the thinnest NaI layers. This effect would be expected if the NaI reacted with the nickel foil and caused the sodium to be distributed throughout the volume of the nickel. The protons emitted from the interaction of deuterons on sodium then would originate from within the volume as well as from the front surface of the nickel and, hence, give rise to the broad peaks observed. No attempt was made to evaporate other sodium salts onto the nickel foils.

TABLE I. Q-values for $Na^{23}(d,p)Na^{24}$ and energy levels in Na^{24}. Columns (a) and (d) = present investigation; Columns (b) and (e) = Whitehead and Heydenburg; Columns (c) and (f) = Kinsey, Bartholomew, and Walker.

Group	Relative intensity (±20 percent) $E_d=2.0$ Mev	Q-values (Mev) (a)	(b)	(c)	Energy levels in Na^{24} (d)	(e)	(f)
(0)	1.0	4.731±0.007	4.77	···	0	0	···
(1)	0.7	4.259±0.007	···	···	0.472±0.008	···	···
(2)	1.4	4.167±0.007	4.23	4.18±0.03	0.564±0.008	0.54	0.55±0.03
(3)	7.0	3.390±0.006	3.45	3.38±0.03	1.341±0.008	1.32	1.35±0.03
(4)	2.5	2.887±0.006	2.94	2.90±0.03	1.844±0.008	1.83	1.83±0.02
(5)	1.4	2.847±0.006	···	···	1.884±0.008	···	···
(6)	0.4	2.267±0.006	···	···	2.464±0.008	···	···
(7)	0.6	2.170±0.006	2.22	···	2.561±0.008	2.55	···
(8)	4.0	1.322±0.005	1.33	1.33±0.05	3.409±0.008	3.44	3.40±0.05
(9)	0.8	1.149±0.006	···	1.13±0.03	3.582±0.009	···	3.60±0.03
(10)	0.7	1.108±0.006	···	···	3.623±0.009	···	···
(11)	0.8	1.083±0.006	···	···	3.648±0.009	···	···
(12)	4.0	0.993±0.005	0.96	···	3.738±0.008	3.81	···
(13)	1.1	0.881±0.005	···	0.88±0.05	3.850±0.008	···	3.85±0.05
(14)	0.9	0.832±0.005	···	···	3.899±0.008	···	···
(15)	1.2	0.802±0.005	0.78	0.77±0.03	3.929±0.008	3.99	3.96±0.03
(16)	0.8	0.547±0.005	···	···	4.184±0.008	···	···
(17)	3.5	0.529±0.005	0.50	···	4.202±0.008	4.27	···
(18)	0.3	0.512±0.005	···	···	4.219±0.008	···	···
(19)	0.2	0.173±0.005	0.13	···	4.558±0.009	4.64	···

[6] Buechner, Strait, Stergiopoulos, and Sperduto, Phys. Rev. **74**, 1569 (1948).

[7] Buechner, Strait, Sperduto, and Malm, Phys. Rev. **76**, 1543 (1949).

[8] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[9] S. Baskin and G. Goldhaber, Rev. Sci. Instr. **22**, 112 (1951).

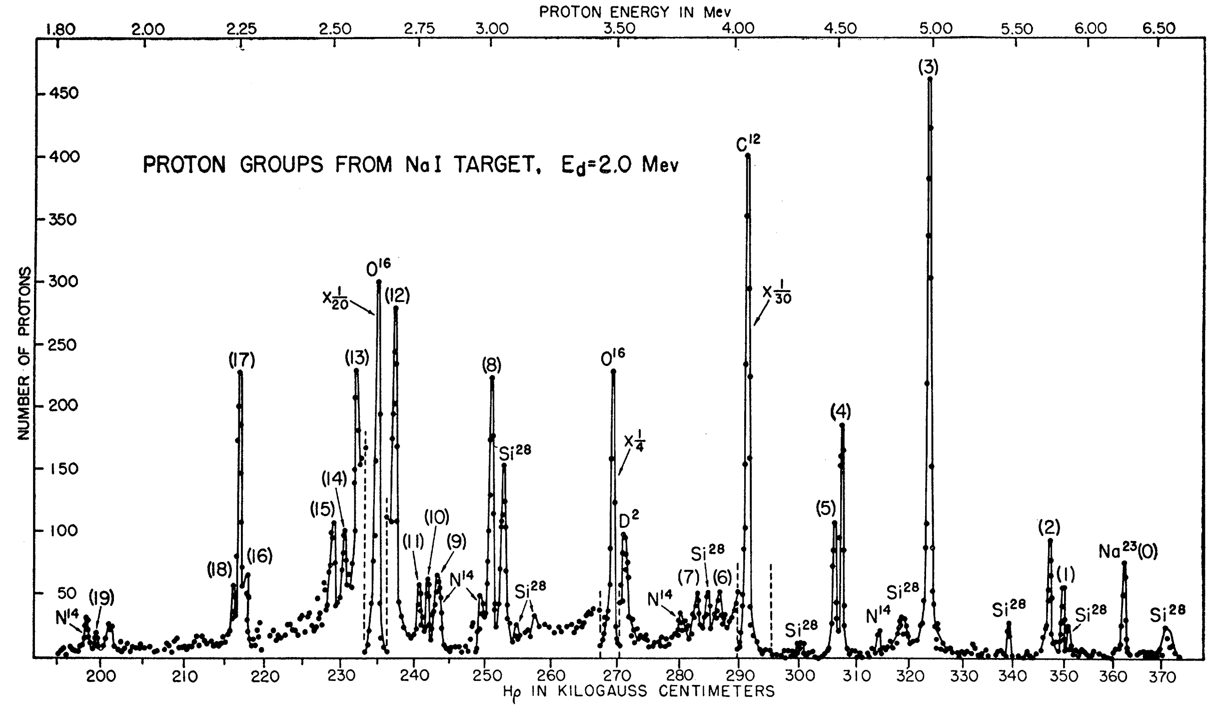

FIG. 1. Proton spectrum observed from deuteron bombardment of thin NaI targets evaporated onto platinum backings. Contamination groups are indicated by the chemical symbol of the target nucleus. Groups from sodium are numbered (0) through (19).

At a deuteron energy of 1.995 Mev, a complete survey was made by bombarding the thin NaI targets for various settings of the magnetic field in the spectrograph. These settings were such that the energy intervals recorded on successive plates overlapped so that a complete spectrum of the particle groups from these targets was obtained on fifteen plates, covering proton energies from 1.8 to 6.5 Mev.

A separate survey was made at a bombarding energy of 1.512 Mev. The observed shift in energy of the various groups was used to assist in the assignment of the groups to the target nuclei responsible. Also, in several instances, bombardments were made at 1.807, 2.105, and 2.214 Mev in the cases where particle groups were not completely resolved for definite identification at 1.995 Mev. The plates were given the same exposure from equivalent targets so that relative yields of the various groups could be estimated. The exposures were measured in terms of amount of charge collected by a fine mesh grid placed just ahead of the target. This charge was related directly to the number of deuterons impinging on the target. A microcoulomb integrating circuit[10] was used for this purpose, and a total of 1000 microcoulombs exposure was used for each plate at the 1.995-Mev run, the time of each exposure being of the order of 1 to $1\frac{1}{2}$ hours. Although both proton and alpha-particle groups were observed, only the proton groups are reported here.

[10] H. A. Enge, Rev. Sci. Instr. (to be published).

II. RESULTS AND DISCUSSION

The complete spectrum of all the proton groups observed at the 1.995-Mev bombarding energy is shown in Fig. 1. The aluminum-foil technique mentioned previously was used in this case for the plates exposed between 195 and 290 kilogauss-centimeters. The peaks identified with reactions from contaminations on the targets are indicated by the chemical symbol of the contaminant nucleus; the peaks assigned to the $Na^{23}(d,p)Na^{24}$ reaction are indicated by the numbers starting with (0), the ground state, through (19), the nineteenth excited level in Na^{24}.

The evidence for assignment for each of the groups was based chiefly on two factors. First, the known contamination groups were identified both by comparing yield ratios of the groups from a particular contaminant observed in the present investigation with those observed in earlier work in this Laboratory from targets enriched in these contaminants and also by comparing the measured Q-values with those previously determined. Second, with the one exception of group (19), the remaining groups assigned to the $Na^{23}(d,p)Na^{24}$ reaction were all observed at least at one other bombarding energy. In each instance, the observed change in proton energy for a given change in deuteron energy was found in excellent agreement with the expected shift.

A total of twenty groups was attributed to various impurities on the target backing; namely, one from the $D^2(d,p)T^3$ reaction, apparently from incident deuterons reacting with other deuterons sticking in the target backing, one from the $C^{12}(d,p)C^{13}$ reaction, two from the $O^{16}(d,p)O^{17}$ reaction, six from the $N^{14}(d,p)N^{15}$ reaction,[11] nine from the $Si^{28}(d,p)Si^{29}$ reaction,[12] and one from a contaminant group that was not identified. Some of the silicon peaks were found troublesome because of their proximity to two of the sodium peaks at the 2.0-Mev bombarding energy.

Many targets were rejected on the basis of having a high silicon contamination relative to the NaI layer. The criterion for acceptance of a target for use in making final measurements from the various groups was based on two factors. First, the sodium-iodide layer had to be sufficiently thin to resolve the close Na(d,p) groups (4) and (5), and second, the silicon contaminant also had to be sufficiently low so that, at the 2.0-Mev bombarding energy, the sodium group (1) was resolved from the close silicon group. The latter separation, at 2.0-Mev bombardment, is 30.8 ± 4 kev, while that of the groups (4) and (5) is 38.7 ± 3 kev. The evidence for the existence of the two sodium groups (1) and (2) was first observed from a target with relatively high silicon content, where group (1) was not resolved from the silicon group and was thus at first attributed to the silicon. However, the presence of an irregularity observed in the shape of the proton-distribution curve gave evidence of the structure later observed from thin-target bombardment. Similar irregularities were also at first observed with groups (4) and (5) and with group (8) and the Si^{28} group at $H\rho$ of about 250 kilogauss-centimeters. Group (9) is broader than the other groups and bombardments at other deuteron energies have shown it consists of two nearly coincident groups, one of which is due to Na^{23} and the other to N^{14}.

The ground-state group (0) was observed at 1.5, 1.8, and 2.0 Mev. Several measurements from different targets gave Q-values agreeing to ±3 kev, the weighted average being 4.731 ± 0.007 Mev. Groups (1) and (2) were also observed at bombarding energies of 1.5, 1.8, and 2.0 Mev, the first excited state observed in Na^{24} being 0.472 ± 0.008 Mev above the ground state. The spacing between the levels corresponding to these two groups is 92.0 ± 3 kev. The fourth group (3) attributed to the Na(d,p) reaction is the most intense of the twenty sodium groups. With 2-Mev deuterons, this group is about 7 times more intense than the ground-state group and about 35 times more intense than the weakest group (19). The level spacing between groups (4) and (5) is 40.3 ± 3 kev. Groups (6) and (7) are relatively weak groups superimposed on the background of protons from the $C^{12}(d,p)C^{13}$ reaction. At the 2.0-Mev bombarding energy, the yield of protons from C^{12} was more than 500 times the proton yield from either sodium group (6) or (7). Despite the presence of these C^{12} protons and the close proximity of Si^{28} and N^{14} groups, groups (6) and (7) were observed also at the 1.5- and 1.8-Mev bombardment. The level spacing between (6) and (7) is 97.1 ± 4 kev.

Between groups (7) and (8), there is a level spacing of 848 ± 8 kev, which is the largest gap in the energy range investigated. This region was also observed at other bombarding energies ranging from 1.5 to 2.2 Mev, so that the likelihood of a proton group from sodium coinciding with a contaminant group may be ruled out. The presence of the two weakest of the Si^{28} groups over the background of protons from O^{16} also indicates that even a fairly weak sodium group would have been detected within this energy range. Therefore, it is concluded that, for the region of excitation in Na^{24} between 2.56 and 3.41 Mev, there is no sodium group with a yield more than about 15 percent of the ground-state group.

In the region of $H\rho$ between 227 and 244 kilogauss-centimeters, there have been identified a total of seven proton groups which are assigned to levels in Na^{24} between 3.582 and 3.929 Mev in excitation, a total separation of only 347 kev. The three groups (9), (10), and (11) were observed at 1.8, 2.0, and 2.2 Mev. At the 2.0-Mev bombarding energy, group (9), which is also labeled N^{14} (Fig. 1), is not resolved from a $N^{14}(d,p)N^{15}$ group. The large half-width and asymmetrical distribution observed at this bombarding energy gave first evidence that this group was complex. It was found that the shape of this group depended on the bombarding energy. With 2.2-Mev deuterons, it separated into two groups, and from the changes in the peak shape with deuteron energy, the higher energy group was assigned to sodium, the Q-value being 1.149 ± 0.006 Mev. That this was the case was confirmed by an exposure at 2.2 Mev on a target free of Na. The high energy group was not observed under these conditions, although the low energy group was seen. Both from the shifts in energy of the groups and the excellent agreement with previous measurements,[11] this low energy peak was assigned to N^{14}. The separation between the levels corresponding to groups (9) and (10) is 41.2 ± 3 kev and is 24.8 ± 3 kev between the levels corresponding to groups (10) and (11).

Groups (12), (13), (14), and (15) were observed at deuteron bombarding energies of 1.5, 1.8, 2.0, and 2.2 Mev. Here again, three of the four groups are observed

TABLE II. Energy-level spacings in Na^{24}.

Level interval (group numbers)	Level spacing (in kev)	Level intervals (group numbers)	Level spacing (in kev)
(0)–(1)	472 ± 8	(10)–(11)	24.8 ± 3
(1)–(2)	92 ± 3	(11)–(12)	89.9 ± 3
(2)–(3)	777 ± 8	(12)–(13)	112 ± 2
(3)–(4)	503 ± 8	(13)–(14)	49.1 ± 2
(4)–(5)	40.3 ± 3	(14)–(15)	30.5 ± 2
(5)–(6)	580 ± 8	(15)–(16)	255 ± 8
(6)–(7)	97.1 ± 4	(16)–(17)	18.3 ± 3
(7)–(8)	848 ± 8	(17)–(18)	17 ± 3
(8)–(9)	173 ± 4	(18)–(19)	339 ± 8
(9)–(10)	41.2 ± 3		

[11] R. Malm and W. W. Buechner, Phys. Rev. **80**, 771 (1950).
[12] Endt, Van Patter, Buechner, and Sperduto, Phys. Rev. **83**, 491 (1951).

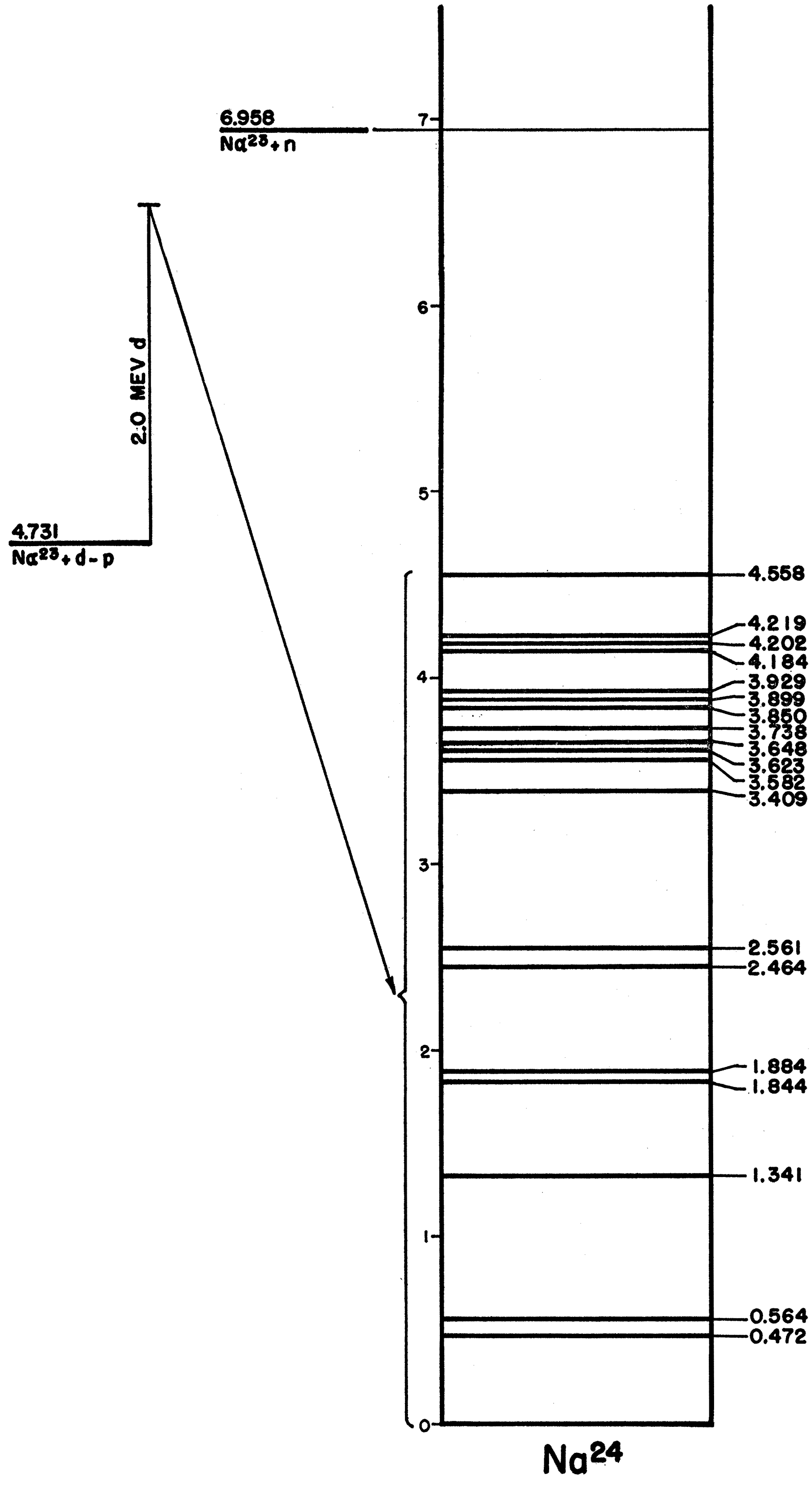

FIG. 2. Energy-level diagram for Na^{24}.

over the background of scattered protons from an $O^{16}(d,p)O^{17}$ group. The Q-values and level spacings are tabulated in Tables I and II.

Measurements on the remaining groups (16) through (19) were based on data from the 2.0-Mev bombardment only. In the region of group (17), several runs were made at 1.8-Mev bombardment with the nickel-foil targets, but because of the target difficulties mentioned earlier, the results were not suitable for precise measurement. Each of two measurements at the 2.0-Mev bombardment of the platinum-backed targets showed three closely spaced groups. Although the three groups were not completely resolved, appropriate adjustments in the peak shapes permitted sufficiently accurate measurements of the Q-values and level separations. The level spacings of 18.3 ± 3 kev and 17.0 ± 3 kev on the two sides of the main group are the closest spacings observed in the present investigation. Because no energy-shift measurement was made in connection with these groups, assignment to $Na^{23}(d,p)Na^{24}$ is based chiefly on the evidence that no common contaminant has been observed in this region at the 2.0-Mev bombardment.

Group (19) is reported here on the basis of a single measurement made at the 2.0-Mev deuteron bombarding energy. It is the weakest of the groups identified with the $Na^{23}(d,p)Na^{24}$ reaction, being of the order of 20 percent the intensity of the ground-state group. Group (19) has not been observed from other targets. The unidentified group to the right of group (19) is presumed to arise from a target contaminant. It has been observed from other targets bombarded in this laboratory, but no definite assignment has been made.

IV. CONCLUSIONS

In Table I, the results of this investigation are summarized and compared with the results of Whitehead and Heydenburg and those of Kinsey, Bartholomew, and Walker. In column 1 are listed the twenty individual groups observed in the present experiment. Column 2 lists the relative yields normalized to the ground-state group. The Q-values and probable errors tabulated in column (a) are the weighted averages of several measurements made at least at two different bombarding energies, except in the cases of groups (9), (16), (17), (18), and (19), as noted above. In column (b) are listed the Q-values obtained by Whitehead and Heydenburg from range measurements and for which no probable errors were given. The figures are the numerical averages of the values they reported at the three bombarding energies 2.0, 2.5, and 3.0 Mev, except for groups (15), (17), and (19), in which cases no values were reported for the 2.0-Mev bombardment. In column (c) are listed the Q-values as deduced by combining the binding energy of the deuteron[13,14] and the ground-state Q-value from the present investigation with certain gamma-ray transitions observed by Kinsey, Bartholomew, and Walker.[15] In columns (d), (e), and (f) are listed the resultant levels in Na^{24} as obtained from columns (a), (b), and (c), respectively.

As can be seen from Table I, there is reasonable agreement between the ten energy levels in Na^{24} found by Whitehead and Heydenburg and ten of the values measured in the present work. The additional ten levels found in this investigation are close to those previously measured and probably would not have been resolved by the range method employed in the earlier work.

In Table II are tabulated the level spacings between successive levels in Na^{24}, as determined from this investigation. In certain instances, it is noticed that the probable error is much less than that for the energy level indicated in column (d) of Table I. This is because the groups in question were observed on the same photographic plate where the major source of error in the level spacing arose from the measurement of the peak location.

In Fig. 2 is shown the energy-level scheme for Na^{24}, incorporating the results of the present investigation. The horizontal lines represent the excitation energies in Mev above the ground state.

We are happy to acknowledge the assistance of the various members of the High Voltage Laboratory during the course of this work. We are especially grateful to Mr. W. A. Tripp, Mrs. Cecilia Bryant, and Mrs. Clara Stucky for reading the photographic plates.

[13] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).
[14] R. E. Bell and L. G. Elliott, Phys. Rev. **79**, 282 (1950).
[15] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).