Energy Levels in Na^{23} and Ne^{20}†

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The energy levels in Na^{23} and Ne^{20} have been investigated by means of the reactions $Na^{23}(p,p')Na^{23}$ and $Na^{23}(p,\alpha)Ne^{20}$. Protons with energies of 7.04, 7.17, and 7.45 Mev were accelerated with an electrostatic generator, and the reaction products were analyzed with the broad-range spectrograph at various angles between 45 and 130 degrees. Proton groups were observed corresponding to levels in Na^{23} at 0.440, 2.078, 2.393, 2.641, 2.705, 2.983, 3.678, 3.850, 3.915, 4.431, and 4.778 Mev. The ground-state Q value for the $Na^{23}(p,\alpha)Ne^{20}$ reaction was determined as 2.370 ± 0.008 Mev. Four other alpha-particle groups were observed, corresponding to levels in Ne^{20} at 1.635, 4.248, 4.969, and 5.631 Mev.

I. INTRODUCTION

The study of the energy levels in Na^{23} was originally undertaken primarily in order to trace the source of certain contaminant groups observed in the proton bombardment of various other target nuclei in this laboratory.[1] A preliminary survey from a sodium target revealed some proton groups not previously reported which presumably arose from inelastic scattering from sodium. In addition, a number of alpha-particle groups were observed with sufficient intensity to warrant measurement. In view of the fact that a level in Ne^{20} at 4.97 Mev is of special interest to astrophysicists[2] in connection with the neon abundance and thermonuclear reactions in stars, it was decided to make a more nearly complete investigation of both the (p,p') and (p,α) reactions from sodium.

Earlier work on the level schemes for Ne^{20} and Na^{23} is summarized by Ajzenberg and Lauritsen[3] and by Endt and Kluyver,[4] respectively. The chief work on Na^{23} was that by Stoddard and Gove[5] from cyclotron bombardment of sodium with 7.26-Mev protons. Stoddard and Gove used a crystal spectrometer to measure the energies of the inelastically scattered protons and covered a range in excitation energy in Na^{23} up to 4.5 Mev. They reported the following energies: 2.10, 2.37, 2.69, 3.01, 3.70, 3.92, and 4.45 Mev. Donahue *et al.*[6] made a careful measurement of the 440-kev state by electrostatic deflection of the inelastically scattered protons from sodium and obtained a value of 0.439 ±0.001 Mev. The first two levels in Na^{23} were also observed in this laboratory a few years ago from magnetic analysis of the alpha particles from the $Mg^{25}(d,\alpha)Na^{23}$ reaction. Endt *et al.*[7] obtained 0.427 ± 0.018 and 2.073 ± 0.015 Mev for these states. A 440-kev gamma ray following inelastic collision of neutrons, protons, and alphas from sodium has been observed in numerous investigations.

Knowledge of the positions of the energy levels in Ne^{20} has been derived mainly from inelastic scattering of protons and deuterons from neon and from the $F^{19}(d,n)Ne^{20}$ and $Na^{23}(p,\alpha)Ne^{20}$ reactions.[3] Except for the latter reaction, most of the measurements have been obtained from use of scintillation counters and photographic plate techniques. Recently, from range measurements in photographic plates of inelastically scattered protons from neon, Freemantle *et al.*[8] reported levels in Ne^{20} at 1.58 ± 0.01, 4.20 ± 0.01, 4.95 ± 0.02, and 5.62 ± 0.02 Mev. With a scintillation spectrometer, Schrank and O'Neill,[9] using 18-Mev protons, observed groups of inelastically scattered protons and reported levels in Ne^{20} at 1.63, 4.26, 4.97, 5.81, 7.45, 7.85, 9.2, and 10.0 Mev. From electrostatic analysis of two groups of alpha particles from the $Na^{23}(p,\alpha)Ne^{20}$ reaction, Donahue *et al.*[6] obtained Q values of 2.379 ± 0.003 and 0.745 ±0.002 Mev, corresponding to the ground-state transition and to a level at 1.634 Mev. In an earlier measurement in this laboratory of the ground-state Q value, we obtained 2.372 ± 0.008 Mev.[10]

In the present experiments, accurate measurements have been made of eleven proton groups corresponding to energy levels in Na^{23} up to 4.8-Mev excitation and five alpha-particle groups corresponding to the ground-state transition and the first four excited levels in Ne^{20}. In the case of Ne^{20}, the study included the region up to about 6.6-Mev excitation.

II. EXPERIMENTAL METHOD AND RESULTS

Thin targets of sodium were prepared by evaporating sodium-iodide onto thin films of Formvar. In order to prevent rupture of these targets upon bombardment,

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[2] A. G. W. Cameron (private communication) and Bull. Am. Phys. Soc. Ser. II, **1**, 191 (1956).
[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
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[5] H. Stoddard and H. Gove, Phys. Rev. **87**, 262 (1952).
[6] Donahue, Jones, McEllistrem, and Richards, Phys. Rev. **89**, 824 (1953).
[7] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[8] Freemantle, Prowse, Hossain, and Rotblat, Phys. Rev. **96**, 1270 (1954).
[9] G. Schrank and G. K. O'Neill, Bull. Am. Phys. Soc. Ser. II, **1**, 29 (1956).
[10] Van Patter, Sperduto, Endt, Buechner, and Enge, Phys. Rev. **85**, 142 (1952).

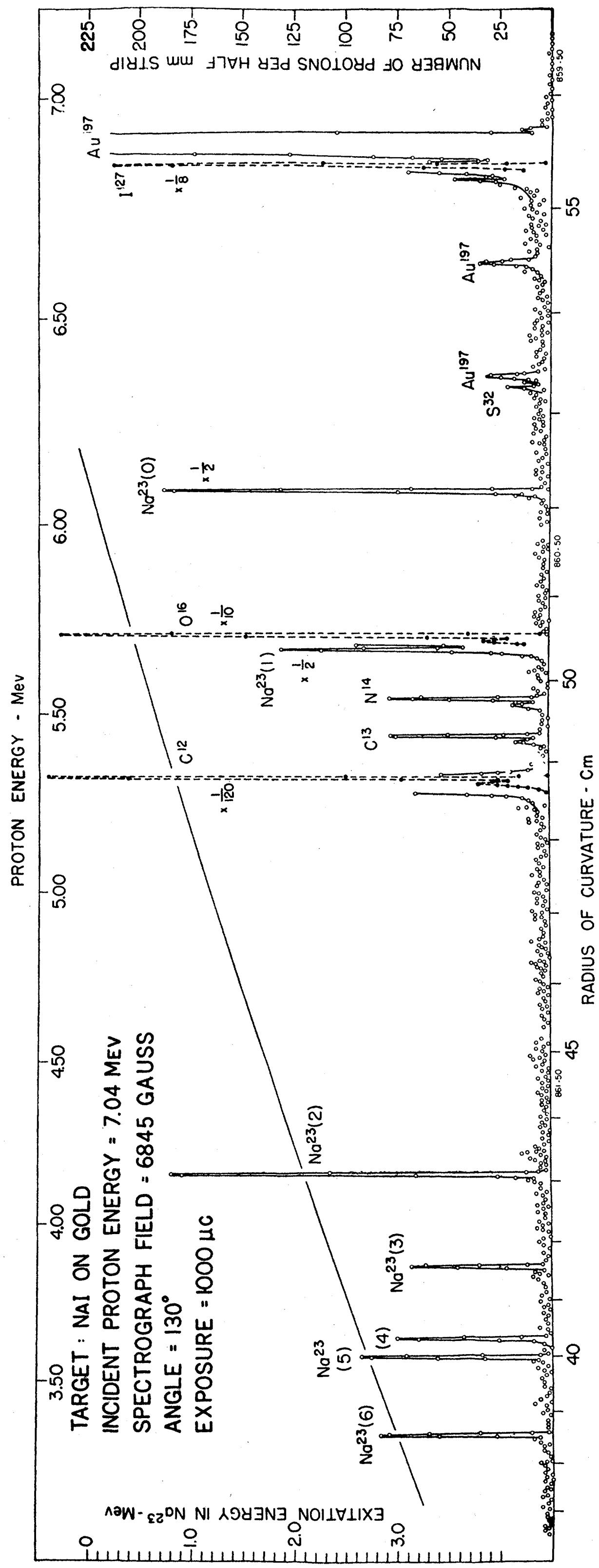

FIG. 1. Spectrum of protons scattered elastically and inelastically at 130 degrees from a thin layer of NaI on a gold backing. The incident energy was 7.04 Mev.

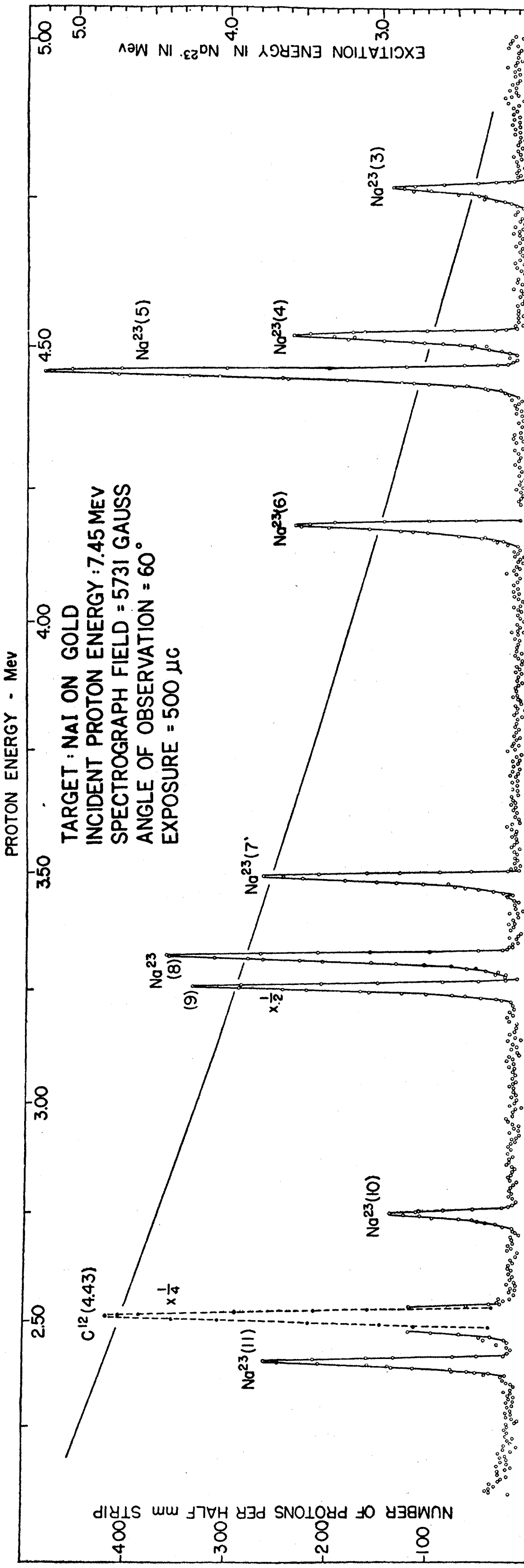

FIG. 2. Spectrum of protons inelastically scattered at 60 degrees from a relatively thick layer of NaI on a gold backing. The incident energy was 7.45 Mev.

TABLE I. Levels in Na^{23} and Ne^{20}.

Level	$Na^{23}(p,p')Na^{23}$ E_x	Rel. intensity $E=7.04$ Mev $\theta_{lab}=130°$	$Na^{23}(p,\alpha)Ne^{20}$ Q value	E_x	Rel. intensity $E=7.04$ Mev $\theta_{lab}=130°$
0	0	100	2.370 ± 0.008	0	100
1	0.440 ± 0.003	81	0.735 ± 0.008	1.635 ± 0.006	309
2	2.078 ± 0.004	36	-1.878 ± 0.008	4.248 ± 0.006	309
3	2.393 ± 0.007	13	-2.599 ± 0.008	4.969 ± 0.006	...
4	2.641 ± 0.007	12	-3.262 ± 0.008	5.631 ± 0.006	...
5	2.705 ± 0.007	17			
6	2.983 ± 0.007	15			
7	3.678 ± 0.007	13			
8	3.850 ± 0.008	5			
9	3.915 ± 0.010	8			
10	4.431 ± 0.010	3			
11	4.778 ± 0.010	...			

a thin layer of gold was evaporated onto the back side. The targets were bombarded with protons accelerated to energies ranging from 7.0 to 7.5 Mev. The charged-particle reaction products from proton-induced reactions on these targets were then analyzed with the broad-range magnetic spectrograph. Elastically and inelastically scattered protons, alpha particles from (p,α) reactions, and deuterons from possible (p,d) reactions from the various target nuclei were thus analyzed and observed in the nuclear emulsions located outside the magnet along the focal plane. The electrostatic generator, the spectrograph, and the general techniques involved in the energy measurements have been described previously.[11,12]

For proper identification of the various particle groups observed on the nuclear-track plates and for accurate energy measurements on each group, data from at least two different bombardments were required. A number of runs (or exposures) at different incident energies and different angles of observation were made, thereby providing sufficient information for identification and measurement. Several NaI targets of different thicknesses were bombarded at least once with proton energies of 7.04, 7.17, and 7.45 Mev. At 7.04 Mev, the reaction particle groups were observed at 130 degrees with respect to the incident beam from targets of two different thicknesses. At 7.17 Mev, one run was made with the spectrograph set to analyze the particles at 90 degrees, and at 7.45 Mev observations were made at 45, 60, and 130 degrees with two different targets being used in the 130-degree run. Except for the 45-degree run, each run consisted of two exposures each with different settings of the spectrographic field. This was done in order to cover a greater range in particle energy on the nuclear-track plate than is possible with a single field setting. For example, in the case of the two field settings used in the 7.45-Mev exposures, after allowing for considerable overlapping, the two sets of exposures provided an energy spectrum ranging from about 2 Mev to 7.5 Mev. This range covered an excitation region in Na^{23} up to about 5 Mev and in Ne^{20} up to about 6.5 Mev.

A spectrum of the protons observed from a typical target is shown in Figs. 1 and 2. Figure 1 shows the protons with energies between about 3.0 and 7.0 Mev scattered elastically and inelastically at 130 degrees from a thin gold-backed NaI target and recorded simultaneously in nuclear emulsion plates placed in the spectrograph. The groups arising from elastic scattering are indicated by the chemical symbol of the target nucleus. In addition to the known deposits of gold, iodine, and sodium, the spectrum shows groups that are due to C^{12}, C^{13}, N^{14}, O^{16}, and S^{32}, all known to be present in the Formvar film backing. No other contaminant nuclei were observed. Two groups from inelastic scattering from gold are observed at distances of 53.3 and 54.4 cm. These correspond to known levels in Au^{197} at 545 and 279 kev.[13] The groups shown by dashed lines were too intense for normal counting from the 1000-microcoulomb exposure. The counting of these groups was made from a 100-microcoulomb run. The groups numbered 1 through 6 are due to inelastic scattering, and the individual energy changes observed at other angles and bombarding energies are consistent with those expected from a target nucleus of mass 23.

Figure 2 shows the proton spectrum observed at 60 degrees and 7.45-Mev bombarding energy from a thicker NaI target. The energy range depicted here is about 2 to 5 Mev, so that all the groups shown are due to inelastic scattering, those numbered 3 through 11 being due to $Na^{23}(p,p')Na^{23}$. The group at a distance of 40 cm has been identified with inelastic scattering from C^{12} leading to the well-known level at 4.43 Mev. The excitation energy of this group, as measured in these experiments, was found to be 4.431 ± 0.008 Mev. The pairs of groups 4 and 5, 8 and 9, and 10 and 11 had not been previously resolved.[5] The excitation energies and the probable errors of all eleven proton groups are listed in Table I. Except in the case of group numbers 10 and 11, each value of excitation energy is the average

[11] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).
[12] Buechner, Mazari, and Sperduto, Phys. Rev. **101**, 188 (1956); C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).
[13] B. Elbek and C. K. Bockelman, Phys. Rev. **105**, 657 (1957).

of at least three measurements. The maximum spread in the calculated energies from each set of measurements was generally less than one-half the quoted error.

In the region of the spectrum shown in Figs. 1 and 2, in addition to the proton group shown, six groups of tracks were observed whose ranges in the nuclear emulsions were appreciably shorter than those produced by protons. Five groups were identified as alpha particles, and all of these were found to be associated with the $Na^{23}(p,\alpha)Ne^{20}$ reaction. One group had track lengths corresponding to deuterons, and these were attributed to the ground-state transition of the $C^{13}(p,d)C^{12}$ reaction resulting from the 1.1% C^{13} content in the natural carbon present in the Formvar backings. An accurate measurement of the Q value for this reaction was made from three different bombardments. The average value was determined to be -2.720 ± 0.007 Mev with a maximum spread of 2.2 kev. Careful measurements of the energies of the alpha-particle groups have been made, and the average Q value and excitation energy from at least two measurements in each case are tabulated in Table I.

III. CONCLUSIONS

Energy-level diagrams of Ne^{20} and Na^{23} are shown in Fig. 3. Only the excitation region covered by the present experiments is depicted in each case. In Na^{23}, the scheme is essentially the same as previously summarized,[4] except that the levels previously indicated at 2.69, 3.70, and 4.45 Mev have been resolved in the present work, each into two levels at 2.641 and 2.705 Mev, 3.678 and 3.850 Mev, and 4.431 and 4.778 Mev, respectively. It is of interest to note from Fig. 1 the high cross sections of the inelastic groups as compared with the elastic group. This has also been observed with all the other sodium bombardments. In Table I are also listed the relative yields of the various inelastic groups with respect to the elastic group for the observations made at 130 degrees and a bombarding energy of 7.04 Mev (spectrum in Fig. 1).

In Ne^{20}, the excitation energies observed here by the $Na^{23}(p,\alpha)Ne^{20}$ reaction are in good agreement with the results obtained from inelastic proton scattering from neon by Freemantle *et al.*,[8] and the present value of 1.635 ± 0.006 Mev for the position of the first excited state is in excellent agreement with the value of 1.634 obtained by the Wisconsin group.[6]

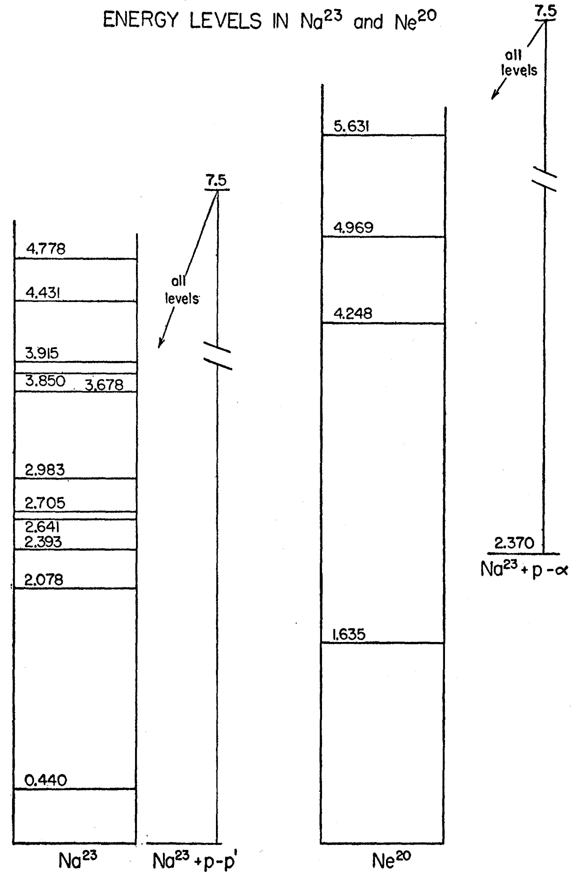

FIG. 3. Energy-level diagrams for Ne^{20} and Na^{23}.

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