Scattering of 22-Mev Alpha Particles by N^{14}†

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(Received September 15, 1955)

The inelastic scattering of 21.5-Mev alpha particles by nitrogen has been investigated. Previously unreported levels at 7.94±0.07, 8.45±0.07, and 10.05±0.07 Mev in N^{14} are observed. Levels at 2.31, 7.4, 7.7, 8.06, and 9.49 Mev reported in other reactions are not observed. This confirms the isotopic spin $T=1$ assignment to the 2.31- and 8.06-Mev levels, and suggests such an assignment for the 9.49-Mev level. The status of the 7.4- and 7.7-Mev levels is uncertain.

I. INTRODUCTION

THE concept of "isobaric" or "isotopic-spin"[1] has proved to be very useful in attempts to relate states of neighboring isobaric nuclei having the same space and spin nucleonic configurations but different charges. For example, in the isobaric triad C^{14}-N^{14}-O^{14}, the 2.31-Mev excited state of N^{14} has been assigned[2] total isotopic spin $T=1$, since it is presumed to correspond to the ground-state configurations of C^{14} and O^{14}. For several isobaric triads, the first isotopic spin $T=1$ state of the nucleus having ground state $T=0$ has been identified, and in some cases (for example, N^{14}) higher $T=1$ states have been found. It is of interest to locate additional states of N^{14} which correspond to states in C^{14} and O^{14}, these N^{14} states representing the $T_3=0$ members of the appropriate isotopic-spin triplets ($T=1$).

Since alpha particles have $T=0$, inelastic scattering of alphas by nuclei with ground state $T=0$ cannot, to the extent that isotopic spin is a good quantum number, excite higher states with isotopic spin $T=1$. With this in mind, the levels of N^{14} have been investigated in two experiments. In the first, a nitrogen gas target was used.[3] This allowed unambiguous assignment of scattered groups to N^{14}, but for various reasons the energy assignments at higher N^{14} excitations were somewhat uncertain. In the second,[4] a melamine target was employed to allow more accurate energy assignments in the region above 7-Mev excitation of N^{14}. These two experiments are reported together in this article.

II. GAS-TARGET INVESTIGATION

A. Experimental Arrangement

The details of the experimental equipment are described in an earlier paper.[5] 21.5-Mev alpha particles accelerated by the Indiana University cyclotron passed through a focusing magnet and an analyzing magnet before striking a target placed at the center of the target chamber. Inelastic alphas scattered from the target were observed by a 20-inch radius point-focusing 180° magnetic spectrometer of the type designed at the California Institute of Technology.[6] The particles were counted by a proportional counter placed just beyond the image slits of the spectrometer.

For this part of the study, the target consisted of nitrogen gas contained in the gas cell shown in Fig. 1. The beam entrance and exit windows were one-inch in diameter and consisted of 0.05-mil nickel and 1-mil aluminum foil, respectively. The exit window for the scattered particles was a multiple-layer zapon lacquer film 0.75 inch in diameter with a thickness of about 0.13 cm air-equivalent. It was oriented so that a particle scattered at 90° in the lab system into the center of the spectrometer acceptance area passed normally through the center of the window. The target volume viewed by the spectrometer was defined by a pair of slits directly outside this window. A thorium B deposit on a button attached to a long rod could be inserted in the gas cell through the gas-inlet pipe to enable the exit-window thickness and the amount of

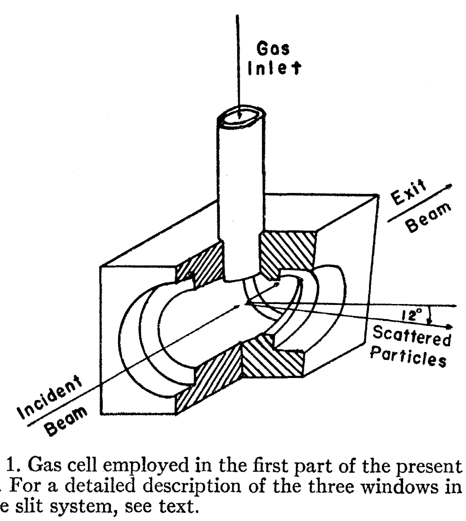

FIG. 1. Gas cell employed in the first part of the present investigation. For a detailed description of the three windows in the cell and the slit system, see text.

† Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] E. P. Wigner, Phys. Rev. **51**, 106 (1937); R. K. Adair, Phys. Rev. **87**, 1041 (1952).
[2] Bockelman, Browne, Buechner, and Sperduto, Phys. Rev. **92**, 665 (1953).
[3] B. M. Carmichael, Indiana University Ph.D. thesis, 1953 (unpublished).
[4] Miller, Gupta, Rasmussen, and Sampson, Phys. Rev. **98**, 1184(A) (1955).
[5] Rasmussen, Miller, and Sampson, Phys. Rev. **100**, 181 (1955).
[6] Snyder, Rubin, Fowler, and Lauritsen, Rev. Sci. Instr. **21**, 852 (1950); W. Whaling and C. W. Li, Phys. Rev. **81**, 150 (1951).

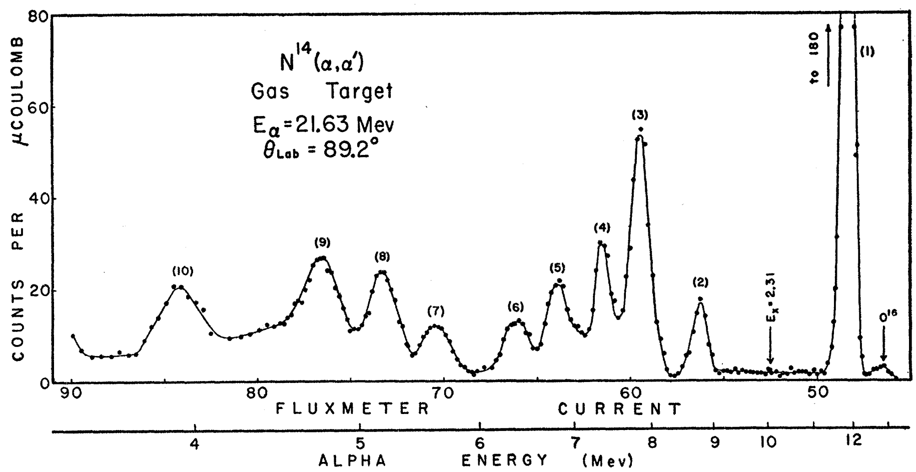

FIG. 2. Spectrum of 21.63-Mev alphas scattered from a nitrogen gas target at a lab angle of 89.2°. The statistical error in each point may be inferred from the ordinate scale (counts per μcoul) and the amount of charge collected per point (4.5 μcoul for the elastic group, 7.5 μcoul for other groups). Note the complete absence of a group exciting the 2.31-Mev $T=1$ state of N^{14}. The Q values for the groups labelled (2) through (6), obtained with the gas target, are listed in Table I. The groups labelled (7) through (10) were studied with a solid melamine target in the second part of the investigation.

gas between the beam path and the window to be measured in terms of the energy loss of 8.78-Mev alphas.

The gas cell could be rotated around the gas-inlet pipe, which coincided with the axis of spectrometer rotation. Even at the extreme available angles of 75° and 105°, the beam hit only the thin exit and entrance windows as verified both by visual observation through the beam-defining slits and by marks left on these windows by the beam. Neither of these windows was viewed by the spectrometer.

The nitrogen gas employed had a purity of 99.9 percent, according to the manufacturer's analysis (The Matheson Company). A search for elastically scattered alphas by contaminants at a lab angle of 89.2° revealed no trace of carbon, but variable amounts of oxygen were found with up to two mole percent abundance (as subsequently checked using CO_2 in the gas cell). This oxygen impurity was probably due to slow leaks or desorption of air from the walls of the gas-cell filling system. It seems very unlikely that it contributed anything but the elastic peak to the observed spectrum.

B. Results

The alpha spectrum from the nitrogen gas target was obtained at three laboratory angles of observation: 75.0°, 89.2°, and 104.7°. A typical spectrum of the scattered alpha groups is shown in Fig. 2. The elastic group from N^{14}, which was found to be the highest intensity group at all three angles, was used throughout the experiment to determine the beam energy. In general, the elastic group was run before and after each lower-energy group. Each excited state was checked two or more times by this procedure. The data from the separate runs (adjusted to a standard beam energy) were combined to produce the spectrum shown in the figure.

The groups in Fig. 2 labeled (1) through (6) represent elastic and inelastic excitation of N^{14} to most of its known excited states up to and including 7-Mev excitation. The Q-values calculated from the group energies are compared in Table I with the excitation energies compiled from other reactions.[7] Three corrections have been made in calculating the Q's of Table I. The first two are the usual corrections for relativistic effects and target thickness. The third correction is for a nonlinear relation between the average magnetic field in the spectrometer and the field indicated by the fluxmeter. The magnitude and sign of this correction suggest that at high fields, the average field is somewhat higher than that at the fluxmeter coil position, which is probably an indication that the fluxmeter coil is too close to the edge of the field region although there is some possibility that local inhomogeneities in the field may also contribute. The magnitude of this nonlinearity has been checked by comparing the 6.042-, 6.082-, and 8.776-Mev alpha lines from a ThB deposit.[8] If the 6-Mev lines are taken as the standard, a correction of 17 kev must be added to the value obtained for the 8.78-Mev line. A check covering a much wider range was obtained by slowing the 6-Mev alphas from ThB down to around 4 Mev with an aluminum foil, and observing both He^{+} and He^{++} ions. This gave a correction for 16-Mev alphas of 200 kev.[9] The accurately measured Q of -3.945 ± 0.005 Mev for the second excited state of N^{14} quoted by Bockelman *et al.*[2] and the gas-target data for the corresponding alpha group at 75°, 90°, and 105° were then used to interpolate between these corrections. The correction curve below 6 Mev remains somewhat uncertain. However, the results obtained with C^{12} recoil ions, as shown in Fig. 7 of reference 5 (where the 6^{+}, 5^{+}, and 4^{+} charge states

[7] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[8] $B\rho$ values of 354.11, 355.26, and 426.83 kilogauss-cm were used. See W. B. Lewis and B. V. Bowden, Proc. Roy. Soc. (London) **A145**, 235 (1934) and G. H. Briggs, Proc. Roy. Soc. (London) **A157**, 183 (1936).

[9] It should be mentioned that because the equilibrium ratio of He^{+} to He^{++} is very rapidly established, the two charge states will have identical energy spectra and thus should be focussed at magnetic fields differing by exactly a factor of two, except for the minor correction resulting from the electron in He^{+}.

TABLE I. Excitation energies for states of N^{14} obtained in the gas-target investigation, as compared with those obtained from other reactions.[a] Because of possible systematic errors, the error assigned to the average Q is taken as the error on a typical run.

Alpha group	Present investigation 75.0°	89.2°	104.7°	Average	Other[a] reactions
	...	...	...	...	2.31
(2)	3.92±0.05	3.98±0.04	3.95±0.04	3.95±0.04	3.95
	...	...	...	...	4.91
(3)	5.16±0.08	5.15±0.07	5.07±0.05	5.12±0.07	5.10
	...	...	...	...	5.69
(4)	5.84±0.08	5.77±0.07	5.77±0.06	5.79±0.07	5.83
	...	...	...	...	5.98
	...	...	...	...	6.23
(5)	6.45±0.10	6.50±0.07	6.44±0.08	6.47±0.09	6.44
(6)	7.00±0.08	7.04±0.08	7.02±0.08	7.02±0.08	7.02

[a] See reference 7.

fall at fluxmeter currents that are quite close to the required 6:5:4 ratio), indicate that there is no gross error down to an equivalent alpha-particle energy of around 4 Mev.

Groups corresponding to several of the known levels of N^{14} below 7 Mev are not observed. The 2.31-Mev $T=1$ level is among these, as expected (the intensity of the corresponding alpha group is <5 percent that of the group exciting the 3.95-Mev level at 75°). The other missing groups fall close to observed groups, so that not too great a reduction in intensity would account for the failure to observe them. In fact, the "background" on which groups (3) through (6) are superimposed suggests that additional unresolved groups must be present.

Above 7-Mev excitation in N^{14}, the correspondence between known levels and observed alpha groups becomes more difficult to establish. There are two reasons why this is not unexpected. First, the corrections for energy loss of the scattered alphas in the target gas and the exit window become rather large (for 8.78-Mev alphas, these losses are 83 kev and 58 kev, with significant uncertainties due in part to lack of knowledge of the exact beam location and size). Second, the fluxmeter linearity corrections become more important since the immediate reference group, that is the elastic group used to establish the beam energy, is quite far away.[10]

In view of these uncertainties, one is inclined immediately to identify groups (7) and (8) in Fig. 2 (calculated Q's from gas-target data of -8.01 and -8.52 Mev) with known N^{14} states at 8.06 and 8.62 Mev. However, the 8.06-Mev state has been assigned isotopic spin $T=1$,[11] so that no group corresponding to excitation of this state should be found in the present experiment if isotopic spin is rigidly conserved. This raises the following basic question: (a) does the observed group actually result from inelastic excitation of N^{14} to 8.06 Mev, which would mean that the selection rule is being violated, or (b) does the observed group result from inelastic excitation of N^{14} to a new state, previously unreported, which would mean that no selection-rule violation is indicated? The melamine-target investigation was undertaken partly to answer this question and partly to investigate the other groups representing excitation of N^{14} higher than 8 Mev.

[10] Further, the correction curve used is now believed to have been somewhat in error in the low-energy region.

[11] A B. Clegg and D. H. Wilkinson, Phil. Mag. 44, 1269 (1953).

III. MELAMINE-TARGET INVESTIGATION

A. Experimental Arrangement

Melamine was chosen for the solid target material because of the relatively high concentration of nitrogen present in the compound ($N_6C_3H_6$).[12] It had the further advantage that the well-known 4.43- and 9.61-Mev states in the carbon present in the melamine provided convenient alpha groups for the determination of the beam energy. The beam-calibration and Q-determination groups were therefore much closer together than in the gas-target work, where the beam energy was always calculated from the position of the elastic peak from nitrogen.

To prepare the solid targets, melamine powder was compressed into a thin slab and warmed by radiation heating in vacuum.[13] At relatively low temperatures, the melamine sublimed and deposited on thin target backings of aluminum evaporated on zapon. These melamine targets had a total thickness of about 45 kev for beam alphas. They stood up well under bombardment in most cases, although slight flaking occurred on some of the targets. The experimental arrangement for the melamine-target work was identical with that used in the gas-target experiment, except that the gas-target assembly was replaced by a sliding multiple-target holder.

Although the gas-target observations were limited to an angular range from 75° to 105° lab, the melamine-target observations could be carried out at any lab

TABLE II. Excitation energies for states of N^{14} obtained in the melamine-target investigation. Because of possible systematic errors, the error assigned to the average Q is taken as the error on a typical run.

State	Lab observation angle	Calculated Q	Average Q
7.01	90°	7.02±0.05	7.01±0.06
	78.7°	6.99±0.07	
7.94	90°	7.93±0.07	
	90°	7.93±0.05	
	90°	7.95±0.06	7.94±0.07
	78.8°	7.93±0.05	
	78.4°	7.99±0.09	
	78.7°	7.92±0.08	
8.45	90.0°	8.45±0.07	
	78.7°	8.45±0.07	8.45±0.07
	10.4°	8.45±0.08	
10.05	90.0°	10.05±0.07	10.05±0.07

[12] Suggested by F. Ajzenberg, Phys. Rev. 94, 409 (1954), and private communication.

[13] Melamine powder, of high purity, was obtained from Distillation Products Industries (Division of Eastman Kodak), Rochester 3, New York. It might be mentioned that it was necessary to remove all oil from the pumps and clean the vacuum system thoroughly after a series of melamine evaporations before it could be used for other types of evaporations.

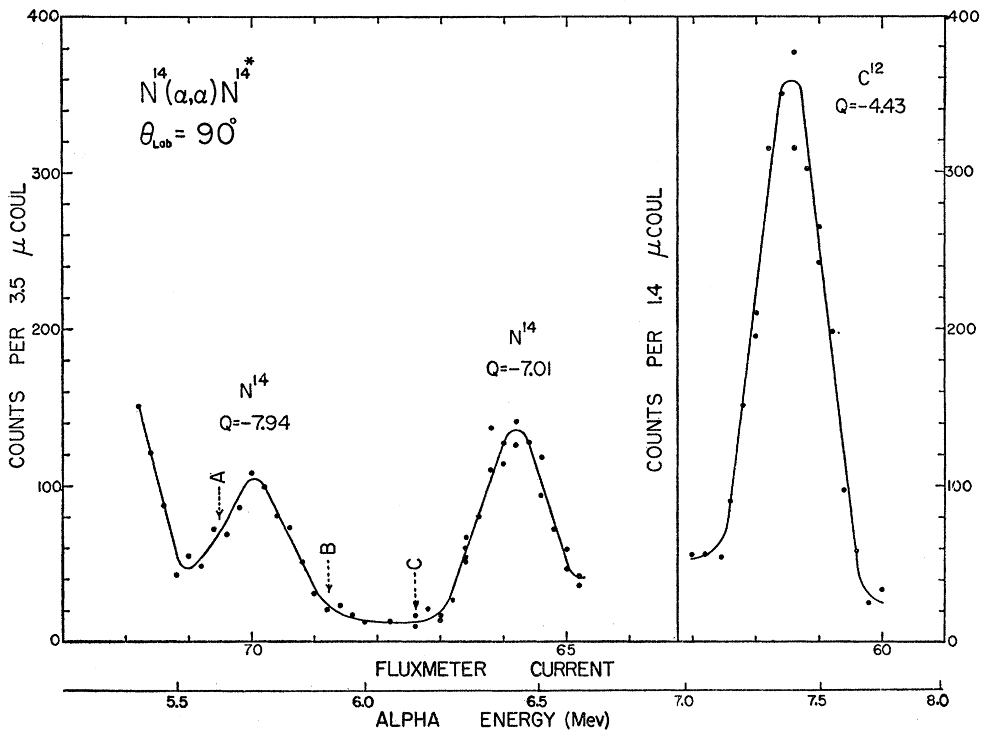

FIG. 3. Portion of the spectrum of 21.5-Mev alphas scattered inelastically from a melamine target at a lab angle of 90°. The peak at the right of the figure represents the alpha group exciting C^{12} to 4.43 Mev, which was used to determine the beam energy, while the two peaks at the left represent groups exciting N^{14} to 7.01 and 7.94 Mev, and correspond to groups 6 and 7 of Fig. 2. There is no evidence for a group (at A) exciting N^{14} to its well-known 8.06-Mev state, nor for groups (at B and C) exciting N^{14} to states at 7.72 and 7.40 Mev as quoted in reference 7.

angle between 10° and 145°. However, because of the overlapping of groups scattered by carbon and nitrogen, the only laboratory angles used were 90°, 78.5°, and 10.4°. The 78.5° position was especially useful because at this angle the inelastic alpha group (from the 4.43-Mev C^{12} state) used for determining the beam energy falls at the same magnetic field as the 8.78-Mev ThC′ alpha group used for calibrating the fluxmeter, and because the most interesting N^{14} group lies between this field and the field corresponding to the 6-Mev ThB lines. Any possible effects of fluxmeter nonlinearity were thus minimized. All Q determinations were made by first running the calibration C^{12} group, then the N^{14} group in question, and then the C^{12} group again, in order to guard against beam shifts, etc. When portions of the spectrum that could be compared with the gas-target data were run, the results were essentially identical except for the carbon groups, thus verifying the nitrogen group assignments.

B. Results

A summary of the Q-values calculated from acceptable group runs is shown in Table II. It will be noted that no consistent shift of the calculated Q-values with change of angle is observed. The same three corrections discussed in the gas-target experiment have been applied in obtaining the Q's in Table II. However, the linearity correction here is much less important because the beam energy and Q-determination groups were much closer together. Because of the way in which the experiment was performed (using C^{12} and N^{14} groups from the same melamine target), errors due to angle determination (probable error $\pm\frac{1}{4}°$) and target-thickness measurement are negligible. Because there is always the possibility that unknown systematic errors might enter in, the error assigned to the *average* Q quoted in each case is essentially the probable error on a single run.

A typical curve obtained at a laboratory angle of 90° is shown in Fig. 3. The large peak widths indicated in the figure (1.6% in momentum) may be accounted for

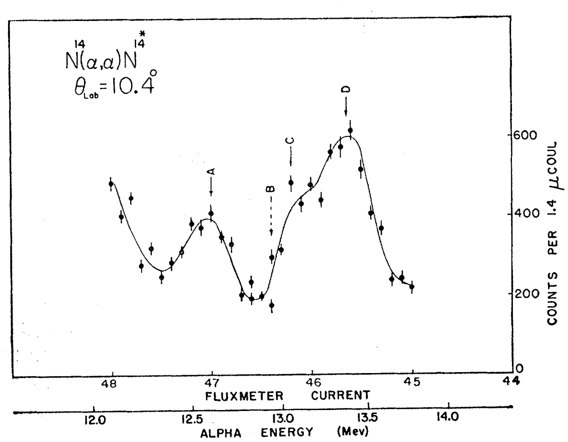

FIG. 4. Portion of the spectrum of 21.5-Mev alphas scattered inelastically from a melamine target at a lab angle of 10.4°. Arrow D represents the location of the alpha group exciting C^{12} to 7.68-Mev, as determined by a graphical subtraction, which was used to calculate the beam energy. The predicted locations of alpha groups exciting N^{14} to 8.45 and 7.94 Mev are shown by arrows A and C respectively, along with the predicted location of a group exciting N^{14} to 8.06 Mev (B) which is not observed.

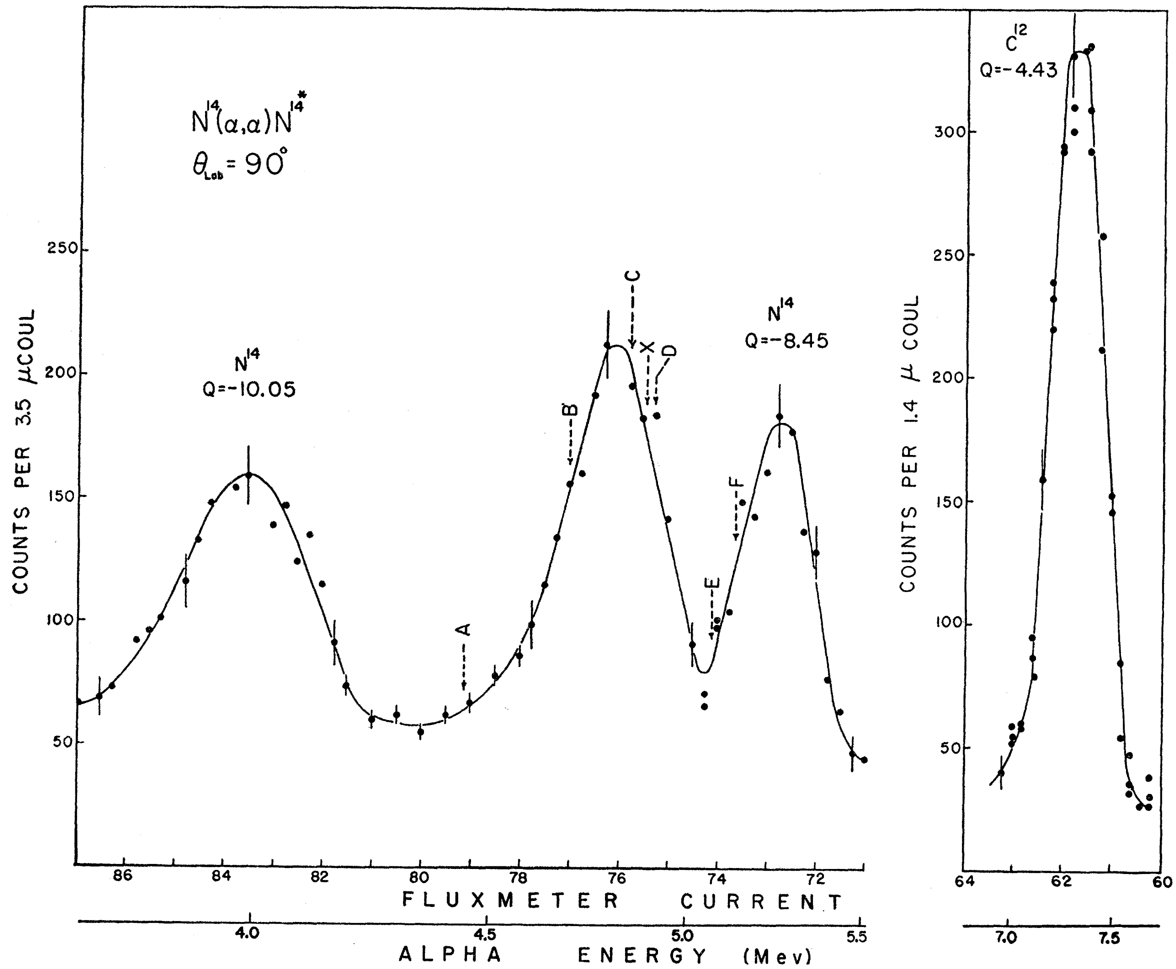

FIG. 5. Portion of the spectrum of 21.5-Mev alphas scattered inelastically from a melamine target at a lab angle of 90°. The peak at the right of the figure represents the alpha group exciting C^{12} to 4.43 Mev, which was used to determine the beam energy. The arrows represent predicted locations for alpha groups exciting N^{14} to the following known states: *A*—9.49 Mev, *B*—9.17 Mev, *C*—8.98 Mev, *D*—8.90 Mev, *E*—8.70 Mev, and *F*—8.62 Mev. A group exciting C^{12} to 7.68 Mev is also predicted at the position indicated by *X*. Two new states (or multiplets) at 8.45- and 10.05-Mev excitation in N^{14} are indicated. The three nitrogen groups correspond to groups 8, 9, and 10 of Fig. 2. Statistical errors for representative points are indicated by vertical lines.

almost entirely by the variation in energy of the scattered particles over the large solid-angle accepted by the spectrometer. The inelastic alpha group at the right in Fig. 3, leaving C^{12} in its 4.43-Mev excited state, was used for the beam-energy determination. The central alpha group in the figure results from excitation of N^{14} to 7.01±0.06 Mev, calculated from a *Q*-run at 78.5° and one at 90° lab. This result is in good agreement with the excitation energies of 7.00±0.04 quoted by Benenson,[14] who observed neutron groups from the $C^{13}(d,n)$ reaction, and 7.05±0.04 quoted by Bent *et al.*[15] who observed γ rays from the $C^{13}(d,n)$ reaction.

The alpha group studied most carefully in the present investigation was the group at the left of Fig. 3, since it falls close to the location expected for a group leaving N^{14} excited to the known state at 8.06 Mev. On the basis of the six acceptable *Q*-runs (three at 90° and three at 78.5° lab), the calculated *Q* for the group observed at the left of Fig. 3 is -7.94 ± 0.07 Mev. For comparison, a group corresponding to the 8.06-Mev state would be predicted to occur at the position indicated by *A* in Fig. 3.

Further confirmation for the *Q*-assignment to the 7.94-Mev state is given by Fig. 4, which shows the inelastic alpha spectrum at a lab angle of 10.4°. This figure clearly does not allow any accurate estimate of the *Q* to be made because of the overlapping of the alpha groups leaving C^{12} at 7.68-Mev excitation (indicated by *D* in Fig. 4) and N^{14} at 7.94-Mev excitation (indicated by *C* in Fig. 4). On the other hand, since under these conditions the separation of the two groups depends sensitively only on the two *Q*-values involved, and since the 7.68-Mev level in C^{12} seems to be fairly

[14] R. E. Benenson, Phys. Rev. **90**, 420 (1953)
[15] Bent, Bonner, and Sippel, Phys. Rev. **95**, 649(A) (1954) and private communication quoted by reference 7.

accurately located,[16] it is felt that the data of Fig. 4 require a level in N^{14} below 8.0 Mev so that the alpha group in question cannot be identified with the known 8.06-Mev level.

Two other states have been reported in N^{14} in the region of excitation covered in Fig. 3 by Benenson[14] at 7.50±0.04 (questionable) and 7.72±0.04 Mev, while Bent *et al.*[15] report a 7.30±0.05 Mev γ ray. If one assumes[7] states at 7.40 and 7.72 Mev, the corresponding alpha groups in the present reaction should occur at the positions indicated by C and B respectively in Fig. 3. It might be mentioned that a state at 7.94-Mev excitation would probably have been obscured in Benenson's $C^{13}(d,n)$ work by C^{12} contamination.

Figure 5 shows the alpha spectrum at 90° lab corresponding to higher excitation of the residual N^{14} nucleus. The rise at the left of Fig. 5 corresponds to the rise around fluxmeter 72 in Fig. 3. The arrows in Fig. 5 represent expected locations for groups leaving N^{14} in its known excited states (see figure caption). The 8.70-Mev excited state (E) has been assigned isotopic-spin $T=1$, but its width of 500 kev would make it unobservable in this experiment even if a corresponding group existed. The peak around fluxmeter 76 in Fig. 5, whose center corresponds to a calculated Q of -9.03 Mev, is believed to be a composite of groups leaving C^{12} at 7.68-Mev excitation (X) and N^{14} at 8.90 (D), 8.98 (C), and possibly 9.17-Mev (B) excitation (if the 9.17-Mev state is $T=1$ as suggested,[7,17] a new level above 9.03-Mev may be required to explain the peak shape).

The group near fluxmeter 73 in Fig. 5 has a width which is consistent either with one or with more than one close-lying levels in N^{14}. On the basis of three acceptable Q-runs, one each at 90°, 78.5°, and 10.4° (lab),[18] the calculated Q for this group is -8.45 ± 0.07 Mev. This result is inconsistent with any previously reported state in N^{14}.

The very broad peak at the left of Fig. 5 may also represent an average over two or more groups, although no states have been reported[7] near this excitation in other reactions. On the basis of a single Q-run only, taken at a lab angle of 90°, the Q calculated for the center of this peak is 10.05±0.07 Mev.

It should be pointed out that even in runs with improved statistics no clear evidence for the existence of a group corresponding to the 9.49-Mev excited state is indicated at position A in Fig. 5. On the other hand, the existence of a sizeable experimental background in this region precludes ruling out a group from the 9.49-Mev state entirely.

[16] Dunbar, Pixley, Wenzel, and Whaling, Phys. Rev. **92**, 649 (1953); A. Sperduto and W. J. Fader, Massachusetts Institute of Technology Progress Report, May, 1953 (unpublished).

[17] Woodbury, Day, and Tollestrup, Phys. Rev. **92**, 1199 (1953); R. F. Christy, Phys. Rev. **89**, 839 (1953).

[18] The 4.43-Mev C^{12} group was used to determine the beam energy at the first two angles and the 9.61-Mev C^{12} state at 10.4°, but the calculated Q came out the same in all three cases.

IV. DISCUSSION

The investigation of the inelastic scattering of alpha particles by a nitrogen gas target gives results that are consistent with the known level scheme of N^{14} below 7 Mev. Above 7 Mev there are certain inconsistencies that are troublesome, the most important being the possible observation of the $T=1$, 8.06-Mev state, which should not be excited in this reaction.[19] This region was investigated further with a solid nitrogen target, and results in essential agreement with the gas-target work were obtained.

The alpha group that might have corresponded to excitation of N^{14} to 8.06 Mev was investigated most thoroughly. It was established with considerable certainty that this group involved excitation of N^{14} to a new level at 7.94±0.07 Mev rather than the 8.06-Mev level. Further new levels in N^{14} are also found at 8.45 and 10.05 Mev. Such observations in a region that has previously been carefully searched in the $C^{13}(p,\gamma)$ and $C^{13}(d,n)$ reactions are somewhat surprising. The difficulty may be explained, however, when it is remembered that levels of considerably higher spin are available in the present experiment (the center-of-mass kinetic energy is equal to the barrier height for incoming alphas with $L=7$) than in the comparatively low-energy proton and deuteron experiments.

Several previously reported levels in N^{14} are not observed in this experiment. In some cases this is merely an effect of the comparatively poor experimental resolution and therefore of no significance. On the other hand, levels at 2.31, 7.4, 7.7, 8.06, and 9.49 Mev should have been observed if they can be excited by inelastic alpha-scattering. For the levels at 2.31 and 8.06 Mev, the present experiment gives confirmation of the isotopic-spin $T=1$ assignments that have already been made.

A $T=1$ assignment for the 9.49-Mev level is also suggested. The status of the 7.4- and 7.7-Mev states is less clear, since if they are characterized by $T=1$, their analogs in C^{14} should have been observed, and if they are $T=0$, they should have been observed in the present experiment.

V. ACKNOWLEDGMENTS

The authors would like to express their appreciation to Mr. J. R. Rees for a great deal of help in taking the data, to Professor K. W. Ford for the Coulomb excitation calculations, and to Mr. Paul Bobe for aid in making the drawings.

[19] The expressions for Coulomb excitation given by K. A. Ter-Martirosyan, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 284 (1952), which are of course not strictly applicable, give a cross section about one percent of that observed.