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Energy Levels of Al^{27}†

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Proton groups inelastically scattered from Al^{27} were observed with a high-resolution magnetic analyzer. Bombarding energies between 5.6 and 8.4 Mev were provided by an electrostatic generator. Twenty-two levels have been observed up to 6-Mev excitation. Discrepancies with previous work, both as to number and position of levels, appear. A level at 1.777 Mev in Si^{28} was also measured.

I. INTRODUCTION

A FEW of the energy levels of the Al^{27} nucleus have been seen by several investigators,[1] while Reilly *et al.*[2] have made an extensive survey of the levels up to about 5.7 Mev using inelastically scattered protons. Their cyclotron gave a bombarding energy of 8 Mev, and magnetic analyzers measured input and output energies with good resolution.

In connection with other work on the MIT-ONR electrostatic generator, some of the aluminum levels around 5-Mev excitation were observed. The measured excitations did not agree with the published values. In attempting to account for the discrepancy, these levels were measured again with inelastic proton scattering, and this led to an investigation of the whole aluminum spectrum up to 6-Mev excitation. A preliminary report of the present work has been given.[3]

II. EQUIPMENT AND PROCEDURE

The generator and magnetic analyzer gave proton beams of energies ranging from 5 to 8.4 Mev with a spread in energy of 0.1 percent. An 0.5 mm×5 mm entrance slit defined the beam spot on the targets. An annular magnetic spectrograph was used to measure the energy of particles scattered at 90 degrees to the incident beam. The uniform magnetic field of the spectrograph focused the scattered particles onto a nuclear emulsion after a 180-degree deflection. This instrument has been briefly described in a recent paper.[4]

The annular magnet was calibrated with polonium alpha particles, the $B\rho$ for which was taken to be 3.31588×10^5 gauss-centimeters, and the beam analyzer was then calibrated against this magnet using elastically scattered particles. The input energy was remeasured in this way for each run. The magnetic fields were measured with nuclear resonance fluxmeters. The scattering angle was measured by optical means and checked by observing the energy difference between elastic groups scattered from a heavy and a light nucleus (gold and lithium).

Two types of targets were used. For much of the initial survey, thin aluminum-foil targets, which produced an energy spread in the scattered-particle group several times the analyzer resolution, were used. These gave the maximum peak heights and assured detection of weak groups. A thin layer of aluminum evaporated onto thin Formvar was then bombarded, and each of the groups observed from the targets was carefully studied. The energy width of the groups from these evaporated targets was essentially that caused by the effective analyzer resolution. Levels spaced as closely as 15 kev were easily resolved with these targets.

The region of excitation from the ground state to 4 Mev was surveyed at a bombarding energy of 6.57 Mev; from 3.6 to 4.9 Mev, at an energy of 7.04; and from 4.3 to 5.85 Mev, at an energy of 8.17. The region of excitation from 2.7 to 5.3 Mev was also covered at 7.58 Mev, and that from 5.0 to 6.0, at 8.45 Mev. An energy of 5.64 was used in addition to measure the two levels of lowest excitation. With two exceptions, all levels were seen with at least two bombarding energies.

III. RESULTS

Figure 1 shows a composite plot of the proton groups observed from the thin evaporated targets. The regions in the figure where no data are shown were found in the experiments with the foil targets to be free of groups from aluminum. At each bombarding energy, the intensities of the groups from different targets have been normalized against the elastic group. Because of insufficient collimation of the beam, and possibly other effects, the relative intensities do not reproduce well; therefore, the intensities shown should be regarded as approximate.

From the foil-target data (not shown), it can be stated that no groups, other than those shown in Fig. 1, with intensities greater than 5 percent of the first excited-state group appear up to an excitation of 5.3 Mev. From 5.3- to 6.0-Mev excitation, the intensity limit is based on the data shown in the top curve of Fig. 1. In this region, it is possible that a group of about one-quarter the intensity of the weakest one shown could have been missed. There is some evidence for a

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[1] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).
[2] Reilly, Allen, Arthur, Bender, Ely, and Hausman, Phys. Rev. **86**, 857 (1952).
[3] S. F. Zimmerman and C. P. Browne, Phys. Rev. **94**, 749 (1954).
[4] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).

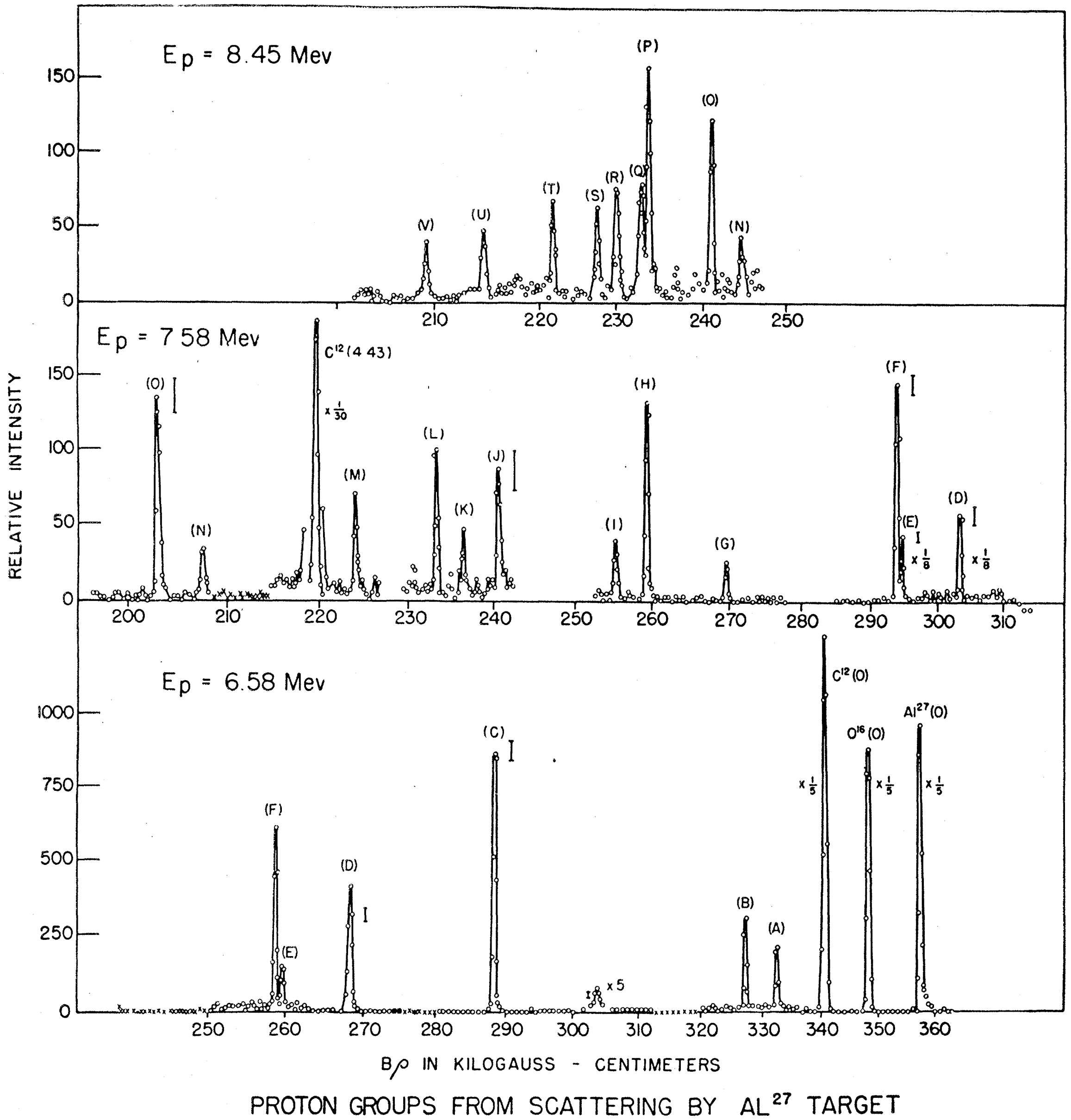

FIG. 1. Composite plot of protons scattered from Al^{27}. Various thin evaporated targets on Formvar backings were used. The peak heights have been normalized to the elastic groups for each target. Regions of excitation in Al^{27} for which no data are shown were observed at other bombarding energies and showed no groups. Groups from excited levels of Al^{27} are labeled alphabetically. Points marked by crosses are from a foil target.

group between groups T and U ($B\rho=218$, Fig. 1). On two exposures at 8.45 Mev, a number of tracks significantly above background appeared. However, on a third exposure at this energy and at a bombarding energy of 8.17, no group appeared in this region of excitation. Another group appeared on one exposure between P and O ($B\rho=237$, Fig. 1), but failed to repeat.

The alphabetically labeled groups in Fig. 1 have been assigned to excited states of Al^{27}. The assignment is based on the constancy of the relative intensity of groups from the foil and evaporated targets and the observation of the change of energy of the scattered group with changing bombarding energy. The region containing the elastically scattered groups was carefully studied to insure that the target did not contain appreciable amounts of contamination other than carbon and oxygen. Since Formvar was used as a target backing, elastic and inelastic groups from carbon and oxygen are to be expected; however, as their energies are well-known, they may be easily identified.

The group labeled V is the only one for which a

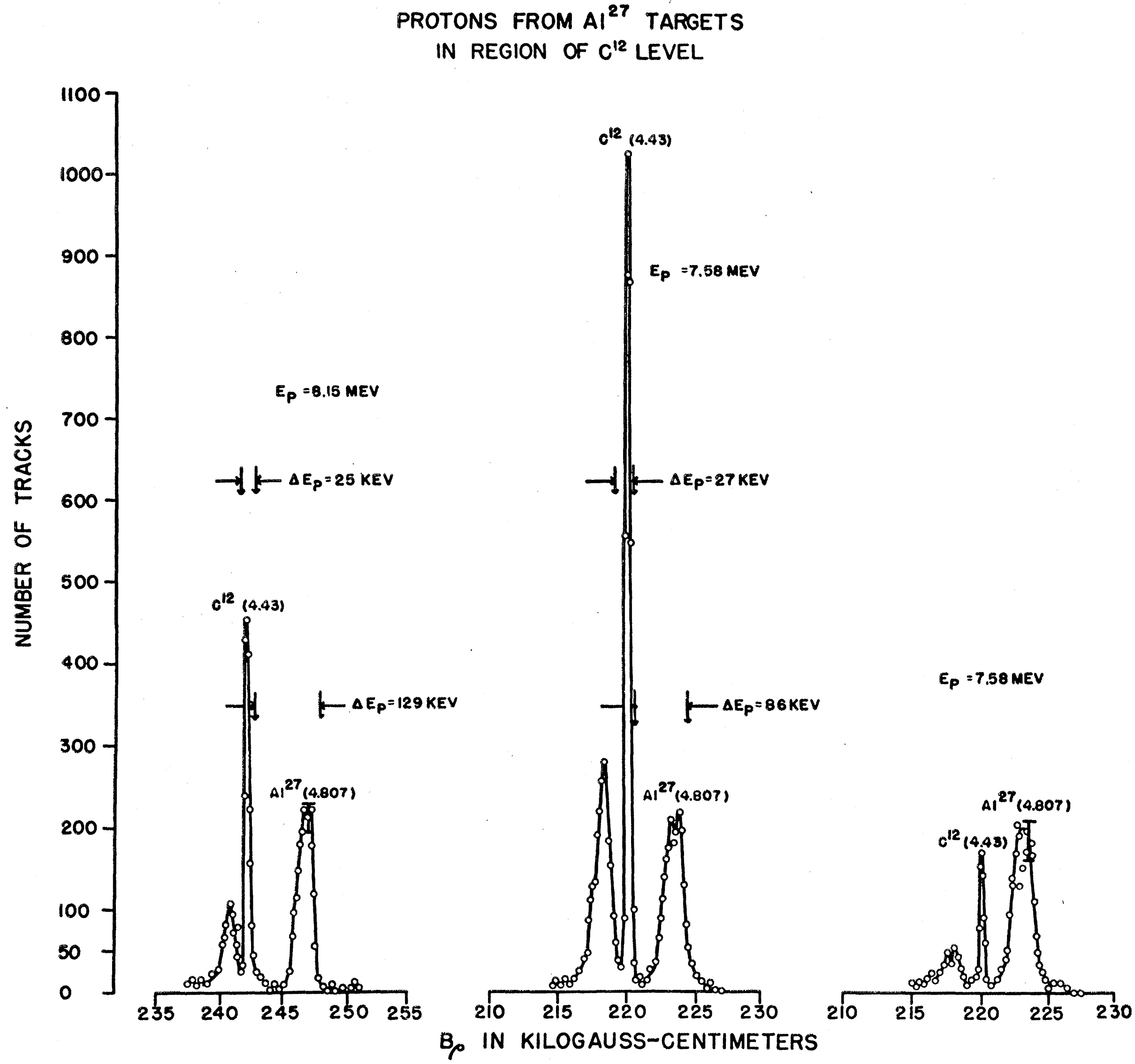

FIG. 2. Evidence for assignment of two proton groups to carbon contamination on front and back surface of aluminum foil target. For explanation, see text.

reservation in assignment must be made. It was observed only once, this being the run shown in the top part of Fig. 1.

In addition to the groups assigned to Al^{27} and to C^{12} and O^{16}, Fig. 1 shows a very weak group at $B\rho=304$ in the lower part of the figure. This latter group has been observed at four bombarding energies between 5.2 and 7 Mev. From its observed change in energy, it may be assigned to a nucleus of mass 28 ± 4. If it is assumed to be from Si^{28}, the excitation is 1.777 Mev. This corresponds to a known level.[5] As a check, a target of evaporated SiO_2 was bombarded immediately after the aluminum. An extremely intense group was found at the same position. Based on the intensity of the group relative to the elastic group from silicon for the SiO_2 target, it was estimated that the amount of silicon contamination on the aluminum target needed to give the observed inelastic peak would give an elastic group that would be lost in the background at the base of the elastic group from Al^{27}. Silicon contamination has been observed before in the annular magnet and might be expected as a contaminant in the foil targets, and it is not surprising to find it here. There is therefore no evidence for an Al^{27} group at 1.8 Mev, as seen by some researchers.[1]

The region containing the group associated with the 4.43-Mev level in C^{12} is of particular interest, as Reilly *et al.* report two levels in Al^{27} that would give groups

[5] R. A. Peck, Phys. Rev. **76**, 1279 (1949); H. T. Motz and D. E. Alburger, Phys. Rev. **86**, 165 (1952).

very near this one at their bombarding energies. In the present preliminary survey, where foil targets were used, two groups were seen in this region. These are shown in the left-hand portion of Fig. 2, together with the group from the 4.807-Mev aluminum level. The bombarding energy here is 8.15 Mev. It is immediately apparent that the central peak is not from the foil material because its width is much narrower than that caused by the foil thickness, as may be seen by comparison with the 4.807 group. This peak was readily assigned to the known C^{12} level from measurements on the change in its energy with a change in bombarding energy. The same three peaks are shown in the middle portion of Fig. 2 for 7.58-Mev bombarding energy. The spacing between the Al^{27} and C^{12} groups has changed the proper amount.

However, the spacing between the C^{12} group and the left-hand group has remained essentially constant, indicating that the left-hand group also cannot come from Al^{27}. It is noted that the energy separation between the two groups is closely the energy thickness of the aluminum foil, and hence it seems apparent that the left-hand group arises from carbon contamination on the back side of the foil. Straggling and nonuniformity of the foil would account for its width. Reilly used a fresh foil in investigating this region and did not report any group from carbon. The right-hand portion of Fig. 2 shows the result of bombarding, at 7.58 Mev, a new foil that had not previously been used. It is seen that the groups assigned to carbon on the two surfaces are greatly reduced in intensity but are still comparable to the intensity of the group from aluminum. The emulsion technique allowed this whole plot to be recorded simultaneously, and undoubtedly this target had considerably less bombardment than Reilly required to plot the region point by point using a counter.

With the thin evaporated aluminum layers on thin Formvar backings, a single intense group is seen from

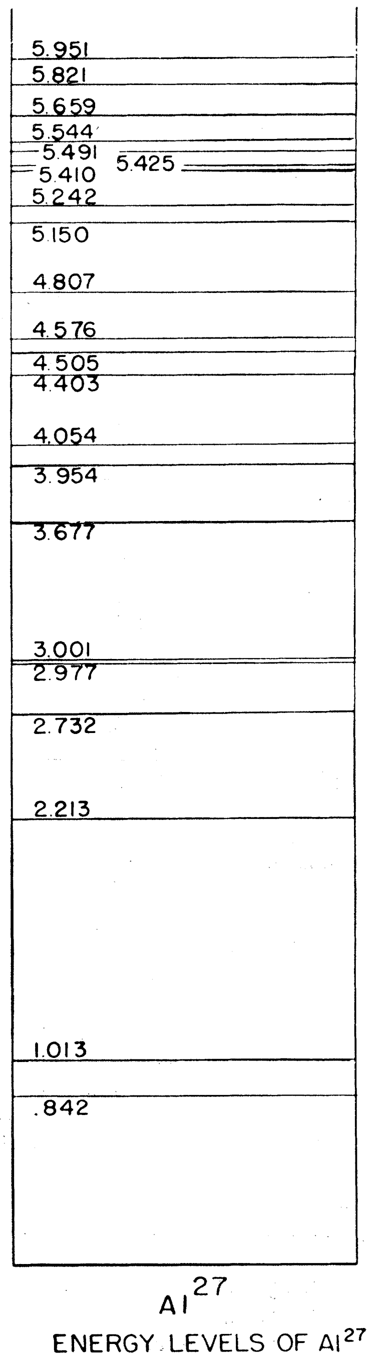

FIG. 3. Energy levels of Al^{27} as determined in this work. Values are in Mev.

TABLE I. Q values for inelastic scattering of protons from Al^{27}.

Group[a]	Q value weighted average all ± 0.006 Mev[b]	Bombarding energies at which observed[c]	Total number of observations used in average[d]
A	-0.842	5.6, 6.57	4
B	-1.013	5.6, 6.57	3
C	-2.213	6.57	2
D	-2.732	6.57, 7.58	3
E	-2.977	6.57, 7.58	2
F	-3.001	6.57, 7.58	2
G	-3.677	6.57, 7.04, 7.58	4
H	-3.954	7.04, 7.58, 8.00	3
I	-4.054	7.04, 7.58, 8.00	3
J	-4.403	7.04, 7.58	2
K	-4.505	7.04, 7.58, 8.16	3
L	-4.576	7.04, 7.58, 8.16	3
M	-4.807	7.04, 7.24, 7.58, 8.16	6
N	-5.150	7.58, 8.16, 8.45	3
O	-5.242	7.58, 8.16, 8.45	3
P	-5.410	8.17, 8.45	2
Q	-5.425	8.17, 8.45	2
R	-5.491	8.17, 8.45	2
S	-5.544	8.17, 8.45	3
T	-5.659	8.17, 8.45	3
U	-5.821	8.17, 8.45	3
V	-5.951	8.45	1

[a] The letters in Column 1 correspond to the peak labels of Fig. 1.
[b] Column 2 gives the Q value which is numerically equal to the excitation energy in Al^{27}.
[c] Column 3 lists the bombarding energies used to measure each group.
[d] Column 4 gives the total number of measurements used in the average for each Q value.

the carbon level, as shown in Fig. 1. The region of excitation in Al^{27} obscured by this group at one energy is clear at other energies. There is no evidence for any aluminum group between the groups labeled M and N.

The measured Q values, which are numerically equal to excitation energies, are listed in Table I. Each number is the weighted average of the values from two to six separate exposures, none of which vary from the average by more than 8 kev. The bombarding energies and number of measurements for each level are given in the last two columns of Table I. The level diagram for Al^{27}, as determined in this work, is shown in Fig. 3.

The discrepancy between the present work and that of Reilly *et al.* is illustrated by the comparison of the level schemes above 4-Mev excitation in Fig. 4. The present values are about 70 kev lower. This difference gradually decreased toward lower excitations, vanishing for the lowest level. As discussed above, no levels are seen between 4.81 and 5.15 Mev. The two levels near 3 Mev with 24-kev spacing and the two near 5.4 Mev with 15-kev spacing were unresolved in the previous work.

IV. ERRORS

Errors involved in the measurements included errors in measurement of group positions on the emulsions, analyzer calibration with polonium alpha particles, determination of scattering angle, measurement of magnetic fields, variation of input energy between measurement of elastic and inelastic groups, and possible effects of target contamination.

It is felt that the major part of the over-all uncertainty stated in Table I arises from errors in determining the radius of the particle trajectory by measurements on the emulsion. This comes from uncertainty in the position of the emulsion both while it is in the spectrograph during exposure and while it is in the microscope during measurement of track positions.

Evidence that the error caused by carbon buildup on the targets is negligible is contained in Fig. 2. The target used to give the groups shown in the center of the figure had been bombarded considerably longer than any target used for final energy measurements. The width of the group from carbon on the surface is still just the analyzer resolution. Thus, the stopping power of the carbon layer cannot be more than a few kilovolts.

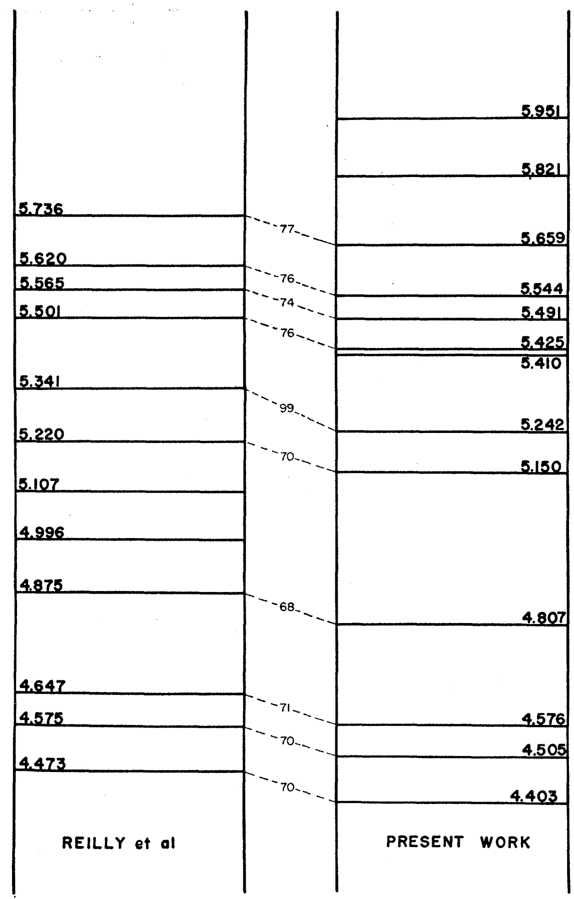

FIG. 4. Comparison of present values and those obtained by Reilly *et al.* for the excited states of Al^{27} above 4.4 Mev. The numbers between the two level diagrams are energy differences in kev.

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