# Energy Level at 31 Kev in $Al^{28}$ from $Al^{27}(d, p)Al^{28}$ Reaction*†

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(Received March 13, 1951)

The proton group previously assigned to the ground state of $Al^{28}$ from the $Al^{27}(d, p)Al^{28}$ reaction has been found to be a doublet, the low energy member of which is ascribed to an excited state at 31.2±2.0 kev. The $Q$-value corresponding to the $Al^{28}$ ground state has been measured as 5.494±0.010 Mev. The $Q$-value corresponding to the ground state of $Mg^{25}$ in the $Al^{27}(d, \alpha)Mg^{25}$ reaction is 6.694±0.010 Mev, and the first excited level in $Mg^{25}$ is at 0.584±0.006 Mev.

## I. INTRODUCTION

ELEMENT number 13, aluminum, exists in nature as a single isotope with mass number 27. Bombardment of aluminum targets with deuterons leads to formation of $Al^{28}$ through the reaction $Al^{27}(d, p)Al^{28}$. $Al^{28}$ decays through $\beta^-$ emission to $Si^{28}$.

The $Al^{27}(d, p)Al^{28}$ reaction was first observed by Lawrence and Livingston[1] in 1934. McMillan and Lawrence[2] subsequently observed five proton and two alpha-particle groups from aluminum targets bombarded with 2.2-Mev deuterons. Livingston and Bethe[3] recalculated the $Q$-values from these observations and found 5.79 Mev for the $Q$-value corresponding to the $Al^{28}$ ground state. A number of papers on this reaction has followed, reporting ground-state $Q$-values of about 5.5 Mev. Range measurements have been used throughout for determining the proton energy, the quoted errors being ±50 kev or higher.

Quite recently, Kinsey, Bartholomew, and Walker[4] have reported a $Q$-value of 7.72±0.02 Mev for the transition to the ground state in the $Al^{27}(n, \gamma)Al^{28}$ reaction. Mobley and Laubenstein[5] have measured the binding energy of the deuteron to be 2.226±0.003 Mev. Combining these two results gives 5.49±0.02 Mev for the $Q$-value corresponding to the ground state in the $Al^{27}(d, p)Al^{28}$ reaction.

The proton groups emitted from aluminum targets bombarded with deuterons have been studied, using the M.I.T. magnetic spectrograph to analyze the proton energy. In order to obtain an accurate determination of the $Q$-values, very thin targets, of the order of 10 kev or less, have been used. The proton peak assigned to the ground state in the first measurements had a configuration in the $H\rho$ diagram that indicated that the group might be a doublet. By improving the resolution of the apparatus, we have been able to separate the two peaks. We assign the upper of these to the $Al^{28}$ ground state and the lower to a low-lying excited state in $Al^{28}$. Other possibilities are ruled out by measurements to be described in the following section.

## II. EXPERIMENTAL ARRANGEMENTS

The apparatus and experimental techniques are essentially the same as those that have been described in a previous paper.[6] Deuterons accelerated in the field of an electrostatic generator are focused and deflected 90 degrees through a magnetic analyzer. After passing a defining slit, the beam hits the target which is placed between the pole pieces of an annular magnet. This annular magnet provides the homogeneous magnetic field for a 180-degree, single-focusing spectrograph. Protons leaving the target at 90 degrees to the incident beam are analyzed in the spectrograph. As recorders, Eastman Kodak NTA nuclear-track plates are used. The tracks are counted under a microscope in strips of 0.23 or 0.50 millimeter in width, and the number of tracks in each strip is plotted *versus* strip distance from the target or *versus* $H\rho$.

As in previous experiments in this Laboratory, polonium alpha-particles were used to calibrate the fluxmeter of the annular magnet. For this purpose, the target was replaced by a silver wire coated with polonium. The value of $H\rho$ for polonium alpha-particles used as an absolute standard was computed from Briggs' value[7] for the $H\rho$ of RaC′ alpha-particles and from Lewis and Bowden's value[8] for the ratio of velocities of RaC′ alpha-particles and polonium alpha-particles. From these measurements, the value of $H\rho$ for polonium alpha-particles is $3.3159\times10^5$ gauss-cm (absolute emu), accurate to 1 part in 5000.

The incident energy of the deuterons was calculated from the observed energy of deuterons elastically scattered from the $C^{12}$ nuclei in a thin Formvar target.

* This work has been supported by the joint program of the ONR and AEC.
† This work was reported at the meeting of the American Physical Society in Chicago, in November, 1950. Phys. Rev. **81**, 317 (1951).
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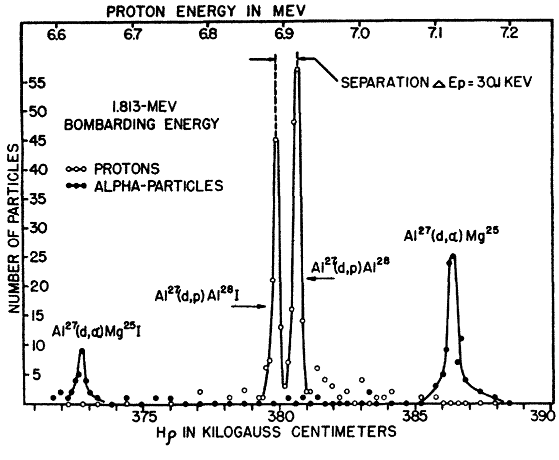


FIG. 1. Proton and alpha-particle groups from thin aluminum target bombarded with 1.813-Mev deuterons.

The aluminum targets employed in these experiments were prepared by evaporating aluminum onto platinum sheets or onto Formvar films supported by nickel-wire frames. Aluminum foils have also been used which were approximately 15 kev thick and were prepared by evaporating aluminum onto Formvar and then dissolving the Formvar in ethylene dichloride. These targets, however, were extremely fragile and were difficult to use.

To improve the resolution of the apparatus, an extra slit of 0.3-mm width was placed in the deuteron beam immediately in front of the target. The resolution obtained was about $\Delta(H\rho)/(H\rho)=7\times10^{-4}$, where $\Delta(H\rho)$ is the half-width of the peak.

### III. RESULTS AND DISCUSSION

Preliminary measurements[9] in this Laboratory with a comparatively thick target yielded a fairly accurate determination of the $Q$-value corresponding to the ground state of $Al^{28}$ but did not disclose the double structure of the proton group.

More than twenty different exposures have now been made with twelve different thin targets in the proper $H\rho$ region for the ground state at 1.2-, 1.5-, 1.8-, and 2.0-Mev bombarding energy. Figure 1 gives $H\rho$ diagrams of the proton and alpha-particle groups on one of these plates. The target for this particular run had a platinum backing, and the bombarding energy employed was 1.813 Mev. The proton doublet shown in the middle of Fig. 1 is consistent on all plates.

The most obvious interpretation of the data is that the right-hand peak in the doublet is associated with the ground state of $Al^{28}$, and the left-hand peak is due to a low-lying excited level. Other possibilities are:

1. The ground-state peak shows as a doublet because of peculiarities in the target, nonhomogeneous deuteron beam, or other instrumental errors; and

2. One of the peaks in the doublet is caused by aluminum; the other, by some contaminant in the target.

It is believed that sources of error of the type listed in item No. 1 may be ruled out by the appearance of the two alpha-particle groups found on the same plates. The two alpha-particle peaks shown in Fig. 1 have been assigned to the $Mg^{25}$ ground state and to the first excited state from the $Al^{27}(d,\alpha)Mg^{25}$ reaction. As far as can be judged with the present resolution of the apparatus, there is no structure in either of these groups. Since they arise from the same target and were recorded simultaneously with the protons and at nearly the same $H\rho$, this lack of structure indicates that the two proton groups are due to nuclear rather than to instrumental effects. As a further control against aberration in the spectrograph, some of the plates were exposed with different settings of the field strength, thereby varying the position of the peaks on the plates. No change in either the appearance or the $Q$-values of the groups was observed.

In order to rule out the possibility that one of the proton groups arose from a contaminant in the target, accurate energy measurements were made on the proton groups at incident deuteron energies of 1.514 and 1.809 Mev. Wide plots of the proton doublet at the two different bombarding energies are given in Fig. 2.

Assuming that the right-hand member is the ground-state peak and the left-hand member is caused by a low-lying excited level in $Al^{28}$, the energy of the level has been calculated. From the 1.514-Mev plate, the energy is $E=31.4\pm0.5$ kev; from the 1.809-Mev plate, it is $E=31.0\pm0.6$ kev. Inasmuch as the values check well within the limits of error, these results do not contradict the assumption that both groups are associated with $Al^{28}$.

Aside from negligibly small correction terms due to relativistic effects and to the fact that the angle of observation is not precisely 90 degrees, a change of $\Delta E_{\text{in}}$ in the bombarding energy causes a change

$$\Delta E_{\text{out}}=\frac{M_{\text{res}}-M_{\text{in}}}{M_{\text{res}}+M_{\text{out}}}\Delta E_{\text{in}}$$

in the energy of the emitted particle. $M_{\text{res}}$, $M_{\text{in}}$, and $M_{\text{out}}$ are the masses of the residual nucleus and incoming and outgoing particles. Using this formula and the separation between the peaks at 1.514-Mev bombarding energy, the separation to be expected at 1.809-Mev bombarding energy has been calculated on the assumption that the right-hand peak is due to $Al^{27}$ and the left-hand peak to $P^{31}$ as target nuclei. The same calculation has been made for $Na^{23}$, and the expected positions of the left-hand peak for the two cases given in Fig. 2. From these calculations, it is concluded that, if one of the peaks is due to $Al^{27}$, the other cannot be due to any nucleus with a mass number outside the region $24 \lesssim M \lesssim 30$. The same experiments and calcula-

[9] K. Huang, B.S. thesis, M. I. T. (June, 1950).

tions have been made using an aluminum-on-Formvar target; the conclusion is the same.

In this mass region, only magnesium, aluminum, and silicon have stable isotopes. Finally, to rule out magnesium and silicon, a search was made for proton groups from such targets in the position of the doublet, but no such groups were found. Special measurements were taken to insure that the yields from the magnesium and silicon targets used were higher than those from the magnesium and silicon contamination in the aluminum targets.

The voltage shift and the test runs have proved that, if one of the peaks in the doublet is due to aluminum, both of them are. From the measurements, it is concluded that $Al^{28}$ has an excited level at $31.2\pm2.0$ kev. The proton yield from the $Al^{27}(d, p)Al^{28}$ reaction assigned to this level is about 55 percent of the ground-state yield and does not vary much with deuteron energies from 1.2 to 1.8 Mev. The $Q$-value corresponding to the $Al^{28}$ ground state in this reaction was measured as $5.494\pm0.010$ Mev, in good agreement with the value of $5.49\pm0.02$ Mev obtained from the combination of the results obtained by Kinsey, *et al.*; and by Mobley and Laubenstein.

Several attempts have been made to verify this excited state using other means. Measurements have been made on the $Si^{30}(d, \alpha)Al^{28}$ reaction, using $SiO_2$ targets enriched in the $Si^{30}$ isotope. (This enriched material was made available by the Stable Isotopes Division, AEC, Oak Ridge.) While the highest energy alpha-particle group observed from this reaction had a greater half-width than would be expected from the appearance of the proton groups from the same target, for reasons of intensity no conclusive measurements have thus far been possible. Also, attempts have been made in collaboration with Mr. N. S. Wall to detect the low energy gamma-rays from this level. These attempts have not been successful because of the high background of radiation from the decay of the other states of $Al^{28}$.

In addition to this unexpectedly low excited state, evidence has been found for a large number of other levels in $Al^{28}$. These appear to have a complicated structure, and considerable further work at the highest resolution will be necessary to establish their locations.

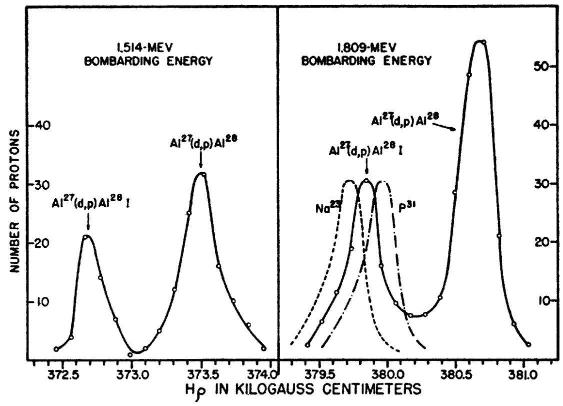


FIG. 2. Proton doublet at two different bombarding energies.

From the alpha-particle groups observed in these experiments, it is calculated that the $Q$-value corresponding to the ground state of $Mg^{25}$ in the $Al^{27}(d, \alpha)Mg^{25}$ reaction is $6.694\pm0.010$ Mev, and the first excited level in $Mg^{25}$ is at $0.584\pm0.006$ Mev. The relative yield for the alpha-particle group assigned to this excited state is about 38 percent of the ground-state yield at 1.5-Mev and 1.8-Mev bombarding energy.

This work was carried out while one of the authors (Harald Enge) was at the Laboratory under the auspices of the 1950 Foreign Student Summer Project at MIT. We wish to express our appreciation to the Student Committee in charge of the program and to the various organizations which collaborated with them in making the program possible. We are also indebted to our colleagues in the High Voltage Laboratory who have collaborated in various stages of this work. We wish to thank Mrs. Cecilia Bryant, Mr. W. A. Tripp, and Mrs. Clara Stucky for their assistance in connection with the reading of the photographic plates.