# Proton Transfer to Specific Final States in the Reaction $Al^{27}(O^{16},N^{15})Si^{28}$ near the Coulomb Barrier

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The angular distribution of $N^{15}$ particles, resulting from the transfer reaction $Al^{27}(O^{16},N^{15})Si^{28}$, was determined at three incident energies, 28.5, 30.0, and 36.0 MeV. The $O^{16}$ ions were accelerated in the Oak Ridge Tandem Van de Graaff. Two silicon-surface barrier counters were placed at the proper angles to detect the $N^{15}$ and $Si^{28}$ particles in coincidence. A proportional counter imposed the further restriction that particles observed in the defining counter be nitrogen nuclei. Angular distributions were determined for two particular final-state transfers: (1) leaving both residual nuclei in their ground states, and (2) leaving the $Si^{28}$ in its first excited state. Within experimental error the two distributions for a given bombarding energy were found to peak at approximately the same center-of-mass angle. By integrating the differential cross sections, the total reaction cross sections, in order of increasing energy, were determined to be: (1) 0.88, 1.35, and 1.37 mb for the ground-state transfers, and (2) 0.96, 1.72, and 2.72 mb for the excited-state transfers. The angular distributions were compared with the predictions of the tunneling theory of Breit bearing in mind that the theory, as formulated, is applicable only to the transfer of neutrons, not protons, and only at incident energies below the Coulomb barrier. As expected, the agreement was found to be better at 28.5 and 30.0 MeV than at 36.0 MeV.

## I. INTRODUCTION

THE single-nucleon transfer reaction, that is the process in which a nucleon makes a transition from one nucleus to another, was first investigated by Reynolds, Scott, and Zucker.[1] With the advent of more heavy-ion accelerators, experimental activity has grown. The scope of the experimental work on transfer reactions, in its present terminology, includes not only the single-nucleon but multinucleon and nucleon-exchange mechanisms. The theoretical aspects of nucleon transfer reactions have been developed by Breit and collaborators[2–5] using the tunneling mechanism, and by Greider[6] using the "$t$" matrix formalism. The tunneling theory, which predicts the initial slope of the differential cross sections, has been applied to the experimental data with varying degrees of success.

The study of the single-nucleon transfer reaction may be arbitrarily divided into two categories. The first is the measurement of total cross-section excitation functions. In the energy region near the Coulomb barrier, typical cross sections of a few tenths to several millibarns are observed for both proton and neutron transfers. The second category is the study of differential cross sections. Early studies of angular distributions employed the technique of stopping the reaction products (the one of interest being radioactive) in an array of suitably placed catcher foils. These early measurements summed contributions from several final states of the reaction. It became obvious that if specific information on the nuclear surface was to be obtained from these reactions contributions from specific final states should be experimentally determined. Using the method of catcher foils, one of the authors (KST) obtained the first angular distribution for a transfer reaction, $N^{14}(N^{14},N^{13})N^{15}$, which left the residual nuclei in definite states,[7] i.e., in this case both the $N^{13}$ and $N^{15}$ were left in their ground states at the time of transfer. One of the authors (EN) recently employed particle detectors to investigate proton transfer reactions proceeding to selected final states in the nitrogen plus boron system.[8]

The present paper presents differential cross sections for the proton transfer reaction $Al^{27}(O^{16},N^{15})Si^{28}$. The Oak Ridge Tandem Van de Graaff Accelerator was used to provide $O^{16}$ ions of 28.5, 30.0, and 36.0 MeV, which correspond to center-of-mass energies of 17.9, 18.8, and 22.6 MeV, respectively. These energies were selected to span the energy region about the Coulomb barrier, which is 18.7 MeV for an $r_0$ of 1.45 F. The experimental arrangement was such that the differential cross sections were individually measured for the case in which both reaction products are left in their ground states (GG), and the reaction in which $N^{15}$ is left in its ground state and $Si^{28}$ in its 1.78-MeV 2+ first excited state (G1st). The target, $Al^{27}$, was chosen because, in addition to the obvious advantage of being monoisotopic, the GG $Q$ value is close to zero and is thus more amenable to comparison with the tunneling theory.

## II. EXPERIMENTAL METHOD

The experimental apparatus and procedure for collecting data is basically the same as that used in a

* Operated for the U. S. Atomic Energy Commission by Union Carbide Corporation.

[1] H. L. Reynolds, D. W. Scott, and A. Zucker, Proc. Natl. Acad. Sci. U. S. **39**, 975 (1953).
[2] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1956).
[3] G. Breit and M. E. Ebel, Phys. Rev. **104**, 1030 (1956).
[4] G. Breit, in *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. 41, Part 1, pp. 367–407.
[5] G. Breit, in *Proceedings of the Second Conference on Reactions Between Complex Nuclei, 1960*, edited by A. Zucker, E. C. Halbert, and F. T. Howard (John Wiley & Sons, Inc., New York, 1960), pp. 1–15.
[6] K. R. Greider, Phys. Rev. Letters **9**, 392 (1962).
[7] K. S. Toth, Phys. Rev. **121**, 1190 (1961); K. S. Toth, Phys. Rev. **123**, 582 (1961).
[8] E. Newman, Phys. Rev. **125**, 600 (1962).

previous study of proton transfer reactions.[8] In brief the system is as follows: A combination $(dE/dx)$-$E$ system is used to take advantage of the fact that for a proton transfer reaction the outgoing particle is of different charge than the elastically scattered particle. A second detector (set at the proper angle so as to detect the recoil particle) is also available to provide for further selectivity.

In the present experiment the $dE/dx$ information is obtained from a gridded ionization chamber which includes a novel approach to the end effects problem. In the energy range under investigation, the heavy-ion ranges are typically on the order of 5 mg/cm². Thus, it is imperative that windows and dead spaces in the $dE/dx$ counter be kept to a minimum. In the present $(dE/dx)$-$E$ counter (Fig. 1), the particles enter the ionization chamber through a 0.62 mg/cm² Ni entrance foil. The silicon surface-barrier counter, 300 Ω-cm $n$-type silicon, is located in the counter atmosphere. The grid is 5-mil diameter Ni wire spaced on 50-mil centers. Normally in such an ionization chamber the repeller is biased negatively, the grid is at ground potential, the collector is at positive potential, and the case is grounded. By using a field plotting device and an electrostatic analog, the equipotential lines within the chamber were determined. From this it was seen that only those ions produced in the region $A-A'$ contribute to the recorded pulse. The electrons produced outside this region are collected on the chamber walls. As may be seen, this represents an appreciable fraction of the total ion path in the counter. It was found from the electrostatic analog that these electrons could be prevented from reaching the chamber walls and instead could be made to contribute to the observed signal at the collector. The upper case was biased to a potential intermediate between the grid and the repeller. For the chamber used here, the upper case was biased at 0.8 $(V_{\rm repel}-V_{\rm grid})$. From $dE/dx$ measurements of elastically scattered $O^{16}$ the observed pulse height was greater by approximately a factor of two when the case was biased than when it was at grid potential. The counter was filled with a mixture of argon and 3% $CO_2$ to a pressure of 12 cm Hg. Gas was flowed continuously at a rate of ≈2 cm³/min and the pressure was regulated with a Manostat. The operating voltages were as follows: collector = +700V, repeller = −220V, and the case = −170V.

A typical $dE/dx$ versus $E$ oscilloscope display is shown in Fig. 2. The detector was at 50° (lab), the beam energy was 30 MeV, and the target was a 125 μg/cm² aluminum foil. The intense group on the oxygen charge locus is the elastic scattering of $O^{16}$ by $Al^{27}$. The weaker high-energy groups are elastic scattering of $O^{16}$ by heavy target impurities. Two distinct groups may be noted on the nitrogen charge locus at somewhat higher and lower energy than the energy of the $O^{16}+Al^{27}$ elastic group. By making coincidences with the recoil particle counter, these two groups were demonstrated to be the GG- and G1-st states of the reaction $Al^{27}(O^{16},N^{15})Si^{28}$. Once the identification of these groups had been made, a gate for a 400-channel analyzer was derived from either a masked oscilloscope face or a single-channel window on the nitrogen line. Details of the method of gating are found in Ref. 8.

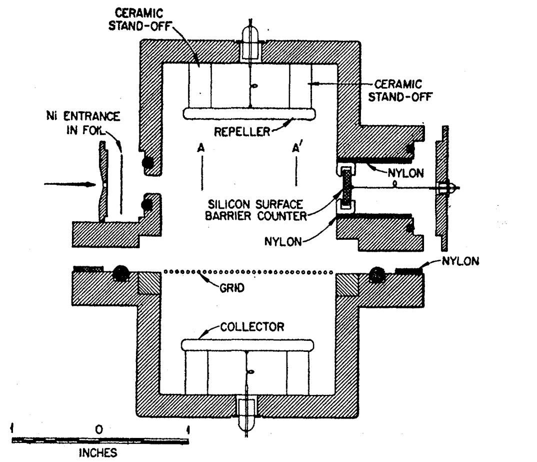


FIG. 1. The $(dE/dx)$-$E$ counter. The scattered particles enter the ionization chamber through a 0.62-mg/cm² Ni entrance foil. After traversing the counter gas, the particles stop in an 300 Ω-cm $n$-type silicon-barrier counter. A mixture of argon and $CO_2$ flows continually through the counter.

### III. RESULTS

Angular distributions were obtained at the three bombarding energies. The six differential cross sections are shown in Fig. 3. The errors indicated in the figure are standard deviations and include only random errors. The accuracy of the ordinate scale is estimated to be ±15%. It is seen that the distributions peak at successively smaller angles as the bombarding energy is increased. At a given energy both states peak at approximately the same center-of-mass angle. The peak value

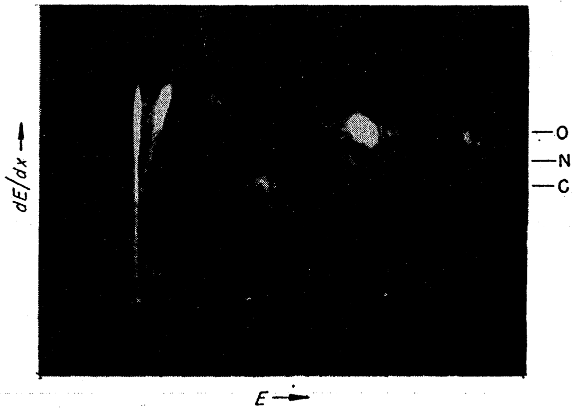


FIG. 2. A typical $dE/dx$ versus $E$ oscilloscope picture at 50° lab. The incident $O^{16}$ energy is 30 MeV. The two groups on the nitrogen charge line are the GG- and G1-st states of the reaction $Al^{27}(O^{16},N^{15})Si^{28}$.

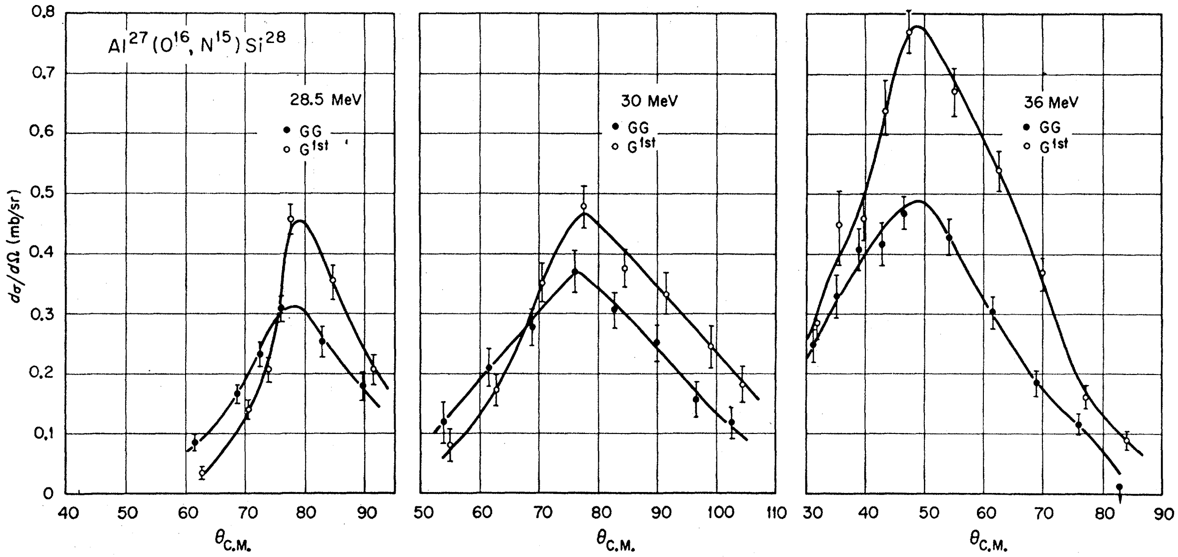


FIG. 3. Differential cross sections for the proton transfer reactions $Al^{27}(O^{16},N^{15})Si^{28}$ and $Al^{27}(O^{16},N^{15})Si^{28*}$ at laboratory energies of 28.5, 30.0, and 36.0 MeV.

of the G1-st distribution is higher than that for the GG distribution at all three bombarding energies. In addition, the small-angle slope of the G1-st distribution is, at each energy, sharper than the slope of the corresponding GG distribution.

The total cross sections for transfer to each state at the three energies were obtained by integrating under the angular distributions. These values are presented in Table I. It is seen that in the investigated energy range the G1-st cross section is larger than the GG cross section and that the G1-st continues to increase as a function of energy whereas the GG levels off. A change in final-state population with varying incident energy has been noted earlier in the study of a neutron transfer reaction.[7] The trend observed previously, however, was opposite from the one seen in this investigation. In the earlier study[7] excited-state transfers appeared to become more prevalent than ground-state transfers as the energy was lowered.

For the determination of the absolute cross section, the value of the average charge of the $O^{16}$ beam (accelerated as 5+) entering the Faraday cup was needed. This was measured by comparing the time needed to collect a given amount of charge when the target was in the beam with that needed when the target was removed from the beam. The average charge values obtained are listed in Table I. These values agree very well with the results of Northcliffe.[9]

TABLE I. Total cross section for transfer to each state.

| Energy (MeV) | Total σ (mb) GG | Total σ (mb) Glst | Average $O^{16}$ charge |
|---|---|---|---|
| 28.5 | 0.80 | 0.96 | 7.00±0.11 |
| 30.0 | 1.35 | 1.72 | 7.05±0.09 |
| 36.0 | 1.37 | 2.72 | 7.09±0.11 |

## IV. DISCUSSION

The tunneling theory of Breit and collaborators[2–5] treats the motion of the initial and final particles by assuming that they travel on classical Rutherford orbits; the motion of the transferred nucleon is treated quantum mechanically. The theory, as currently formulated, is applicable only to neutron transfer reactions which take place below the Coulomb barrier and whose $Q$ values are close to zero. It has, however, been applied to proton transfer reactions[8] with some success despite the fact that theory does not take into account the effect of the Coulomb field on the transferred proton.

To facilitate the comparison between theory and experiment, the distributions shown in Fig. 3 were replotted as $d\sigma/dR_{\min}$ versus $r_0$. The quantity $R_{\min}$ is the distance of closest approach along a Rutherford orbit corresponding to the same angular deflection as that for the observed particle

$$R_{\min}=a(1+\csc\tfrac{1}{2}\theta), \tag{1}$$

where

$$a=Z_1Z_2e^2/2E_{\text{c.m.}}, \tag{2}$$

and

$$r_0=R_{\min}/(A_1^{1/3}+A_2^{1/3}). \tag{3}$$

The relationship between $d\sigma/d\Omega$ and $d\sigma/dR_{\min}$ is

$$d\sigma/dR_{\min}=-(8\pi/a)\sin^3(\tfrac{1}{2}\theta)d\sigma/d\Omega. \tag{4}$$

The tunneling theory predicts that $d\sigma/dR_{\min}$ varies with $R_{\min}$ as

$$d\sigma/dR_{\min}\propto\exp(-\alpha R_{\min}-\bar{\alpha}\bar{R}_{\min}), \tag{5}$$

[9] L. C. Northcliffe, Phys. Rev. 120, 1744 (1960).

where

$$\alpha=[(2M/\hbar^2)E_s]^{1/2};\quad \bar{\alpha}=[(2M/\hbar^2)\bar{E}_s]^{1/2}. \qquad (6)$$

$E_s$ is the separation energy of the transferred nucleon in the delivering nucleus, $\bar{E}_s=E_s+Q$, and $M$ is the mass of the transferred nucleon. $\bar{R}_{\min}$ is calculated in the same way as $R_{\min}$, but by replacing $E_{\text{c.m.}}$ with $E_{\text{c.m.}}+Q$.

The GG- and G1-st differential cross sections, plotted as $d\sigma/dR_{\min}$ versus $r_0$, are shown in Figs. 4 and 5, respectively. For the sake of clarity, the curves in each figure are arbitrarily displaced with respect to one another along the ordinate axis. The values of differential cross section, $d\sigma/dR_{\min}$, are in arbitrary units, the purpose being simply to compare the shapes of the angular distributions with those predicted from theory. The theory does not take into account the onset of compound nucleus reactions at small distances of approach and, therefore, is designed to reproduce only the small-angle (or large-$R_{\min}$) slope of the angular distributions. The predicted slopes are shown in Figs. 4 and 5 as solid lines; these have been drawn normalized to the experimental data. As would be expected from the energy region of validity of the theory, the agreement between experiment and theory is better for the data taken at the two bombarding energies close to the Coulomb barrier than for the results obtained at 36 MeV (4 MeV above the barrier in the center-of-mass system). For the GG transfers the agreement is excellent at 28.5 MeV and becomes progressively worse as

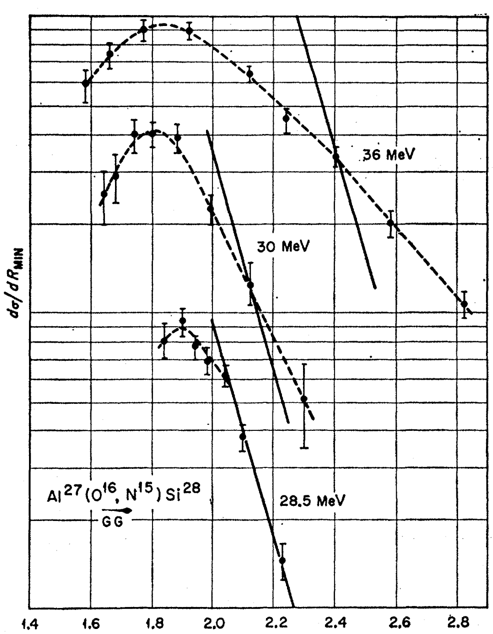


FIG. 4. Differential cross section $d\sigma/dR_{\min}$ versus $r_0$ for the GG distributions at 28.5, 30.0, and 36.0 MeV. The curves have been arbitrarily displaced. The solid curves are calculated from the tunneling theory of Breit as given in Eq. (5) and are normalized to the data.

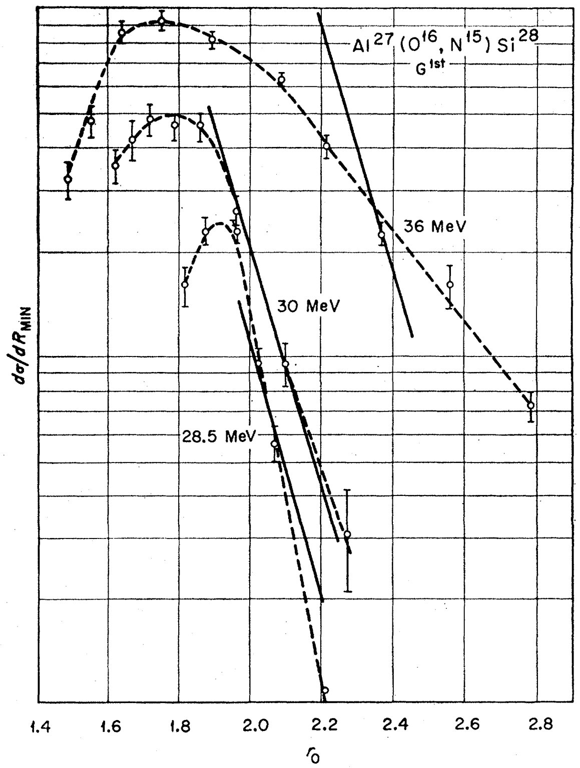


FIG. 5. Differential cross section $d\sigma/dR_{\min}$ versus $r_0$ for the G1-st distributions at 28.5, 30.0, and 36.0 MeV. The curves have been arbitrarily displaced. The solid curves are calculated from the tunneling theory of Breit as given in Eq. (5) and are normalized to the data.

the energy is increased. For the G1-st transfers the same trend can be noted, though in this case the agreement is somewhat better for the 30-MeV data than for the 28.5-MeV results. This same variation with energy of the initial slope of the angular distribution has been observed previously[7,10] in neutron transfer reactions, i.e., as the energy is lowered the experimental small-angle slope becomes steeper and approaches the slope predicted by the tunneling theory.

The peaks in the distributions shown in Figs. 4 and 5 are presumably related to the most probable distance for transfer. The values of $r_0$ obtained in the present studies can be compared with those determined in previous investigations. For GG transfers the value of $r_0$ for the peak of the distribution appears to increase with decreasing incident energy and is in the range of 1.8 to 1.9 F. The same trend with bombarding energy appears to hold also for the G1-st transfers. Here, the peak $r_0$ value ranges from about 1.75 to 1.93 F. These $r_0$ values may be compared with earlier results[7,8] which indicated $r_0\approx 2.2$ F for GG transfers involving as targets the lighter nuclei $B^{10}$ and $N^{14}$. For transfers leaving residual nuclei in excited states earlier investigations have indicated $r_0\approx 1.6$ F.[7,11] Finally, the follow-

[10] K. S. Toth, Phys. Rev. **131**, 379 (1963).
[11] K. S. Toth, Phys. Rev. **126**, 1489 (1962).

ing remarks must be kept in mind. When the $Q$ value is quite different from zero it is not clear whether a correlation can be made between the angle at which $d\sigma/d\Omega$ peaks and the distance of closest approach. It would be expected that particles resulting from reactions with $Q$ values quite different from zero undergo a large deflection. This would not necessarily mean, however, that the transfers took place when the interacting nuclei were close together.

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# Nuclear Elastic Scattering of Monoenergetic Neutron-Capture Gamma Rays*†

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A source of monoenergetic gamma rays produced by neutron capture in various elements is described. A search was made for elastic scattering of these neutron-capture gamma rays from Ta, Hg, Pb, and Bi. A large scattered signal was observed when 7.285-MeV gamma rays produced by neutron capture in iron were incident upon a lead target. Evidence is presented which indicates that this signal results from resonance scattering of these gamma rays by a level in $Pb^{208}$ with an angular momentum quantum number of unity, and with a ground-state radiative width which is less than 4 eV. An argument is presented which indicates that it is probable that the spacing near 7 MeV in $Pb^{208}$ of levels of the type observed is of the order of magnitude of 1400 eV.

## I. INTRODUCTION

NUCLEAR elastic scattering of photons with energies of about 7 MeV has been observed in several investigations.[1–4] In each of these experiments the source of radiation was a continuous one, either the bremsstrahlung from an electron accelerator,[1,3,4] or the Doppler-broadened radiation from a nuclear reaction.[2] In the work of Axel *et al.*[4] a method was employed which limited the energy spread of the beam used to study the scattering process to about 100 keV. The interpretation of these experiments is based on the assumption that at energies below the threshold for particle emission the energy levels in a nucleus are discrete and separated by energies large compared to their widths. The observed photon scattering in this energy range is assumed to result because the incident photon spectrum overlaps one or more of these discrete levels.

In the experiments described in this paper, a search was made for nuclear elastic scattering of photons from the elements, Ta, Hg, Pb, and Bi using as a source of radiation a beam of $\gamma$ rays emitted after neutron capture in various nuclei. The spectra of $\gamma$ rays emitted following thermal neutron capture in various elements have been studied in many laboratories, and two compilations of the results of these studies have been published.[5,6] From a few nuclei the capture $\gamma$-ray spectra consist of one or several intense $\gamma$-ray groups with energies between about 5 and 11 MeV, and a large number of $\gamma$ rays with energies below 5 MeV. These intense, monoenergetic $\gamma$ rays have been used to study some $(\gamma,n)$ reactions,[7] and an arrangement with which a beam of these $\gamma$ rays could be extracted from a reactor has been described by Jarzyck *et al.*[8]

Since the spread of energy of a particular group of $\gamma$ rays emitted in thermal neutron capture is only a few electron volts, it is expected that a search for nuclear elastic scattering of these $\gamma$ rays should check the assumption that nuclear levels below the threshold for particle emission do not overlap. Further, it was hoped that the energies of some of the capture $\gamma$ rays would

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† From the Ph.D. thesis of C. S. Young. A preliminary report of this work was presented in Bull. Am. Phys. Soc. 8, 61 (1963).
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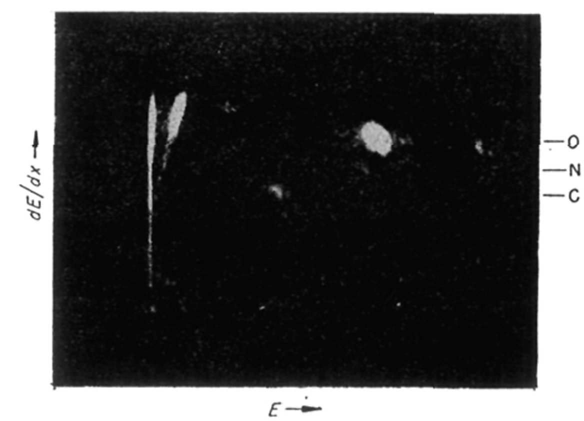


FIG. 2. A typical $dE/dx$ versus $E$ oscilloscope picture at 50° lab. The incident $O^{16}$ energy is 30 MeV. The two groups on the nitrogen charge line are the GG- and G1-st states of the reaction $Al^{27}(O^{16},N^{15})Si^{28}$.