elements for the free-scattering potential components. This should pretty much obviate the range-normalization problem described above. Such a calculation, as a function of energy, is now in progress.[20]

Speaking broadly, it is felt that the results to date of our analysis are encouraging, particularly in view of the strictly exploratory nature of both the theoretical and experimental effort described here. Furthermore it is felt that the points made concerning the inadequacies of the present approach in the preceding paragraph are the only major ones distinguishing our evaluation of V_{pn} from free-body calculations, and methods for remedying most or all of them are not difficult to visualize. Thus we feel it is reasonable to say that exploratory as this work may be it still seems to show that the theoretical method and the experiment are well suited to each other and that, by and large, the direct reaction can and very likely will be useful as another tool in the study of the basic nuclear two-body problem.

ACKNOWLEDGMENTS

We should like to express our gratitude to Mr. Douglas Verdery whose assistance throughout both the experiment and the calculations afterwards was indispensable. Thanks are also due Mr. Bryan Walker for his help during the early stages of the experiment, and to Jack Schaitman and Richard I. Johnson who carried through most of the theoretical computations of the last section. Finally, we should like to thank the entire 90-inch Cyclotron Group for their unfailing efforts and patience on our behalf.

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[20] S. A. Moszkowski and B. L. Scott (private communications).

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$Si^{28}(d,p)Si^{29}$ Reaction*

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The 15-Mev deuteron beam of the University of Pittsburgh cyclotron was used to study the $Si^{28}(d,p)Si^{29}$ reaction. Angular distributions of protons from most of the Si^{29} levels up to an excitation energy of 6.4 Mev were obtained. Good agreement with the 8-Mev deuteron results of Holt and Marsham (at a deuteron energy of 8 Mev) was found, except in a few cases where an $l=2$ distribution showed low-angle peaking in one of the experiments but not in the other. The angular distributions of the 5.94- and 6.19-Mev states in Si^{29}, not previously reported, were obtained. Butler curves with $l=2$ and $l=3$, respectively, were fitted to these two distributions. A somewhat unusual evaporation technique used to prepare the necessary targets from small quantities of SiO_2 with relatively high collection efficiency is described.

I. INTRODUCTION

THE $Si^{28}(d,p)Si^{29}$ reaction has been studied at an incident deuteron energy of 8 Mev by Holt and Marsham,[1] and their experimental results were included in the evidence for the collective behavior of Si^{29} in the study of Bromley *et al.*[2] It is of some interest, however, to perform this experiment at a higher deuteron energy, because the dependence of angular distributions and stripping reduced widths on incident particle energy has been studied in only a few cases. In addition, the use of higher resolution may provide angular distributions to other Si^{29} levels. The work reported here is part of a program carried out in this laboratory to investigate the (d,p) reaction on Si^{28}, Si^{29}, and Si^{30}, and the (d,t) reaction on Si^{29} and Si^{30}. Results of these other experiments will be reported later.

II. EXPERIMENTAL PROCEDURE

The external deuteron beam of the University of Pittsburgh 47-inch cyclotron, whose energy is approximately 15 Mev, is electromagnetically focused and energy analyzed.[3] Charged reaction particles are analyzed by a magnetic spectrometer, which can be rotated about the target. In the present experiment, the reaction protons were detected by means of a nuclear emulsion system.[4]

The targets used were made in this laboratory, as described in the Appendix. One target was made from naturally occuring SiO_2 (92.2% Si^{28}, 4.7% Si^{29}, 3.1% Si^{30}). Other targets enriched in either Si^{29} or Si^{30} were made from SiO_2 enriched in the respective isotope,[5] and

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* Work done at Sarah Mellon Scaife Radiation Laboratory and assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

† Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[1] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 467 (1953).

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[3] R. S. Bender, E. M. Reilley, A. J. Allen, R. Ely, J. S. Arthur, and H. J. Hausman, Rev. Sci. Instr. **23**, 542 (1952).

[4] E. W. Hamburger, Ph.D. thesis, University of Pittsburgh, 1959 (unpublished).

[5] The enriched SiO_2 was obtained from Isotope Sales Department, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

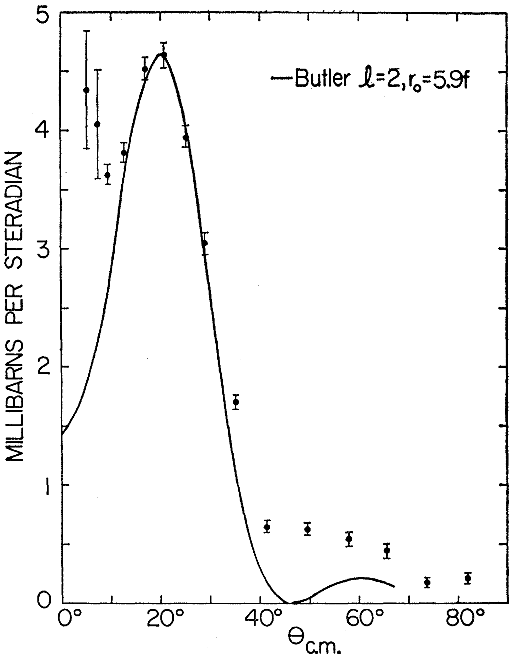

FIG. 1. Angular distribution of the $Si^{28}(d,p)Si^{29}$ 1.278-Mev state.

in the present experiment were used to assign proton groups to the correct isotope and to provide a means of subtracting background counts.

The absolute cross-section scale, discussed briefly in the Appendix, is believed to be accurate within ±30%. The relative cross-section scale should be accurate within ±10%.

For the cases in which backgrounds could be determined in a statistical manner, the error bars in the angular distributions indicate standard deviations. Often a background could not be determined in this manner, in which case an upper limit to the background error was estimated and included in the determination of the total error for the point.

III. RESULTS

Most of the angular distributions obtained in the present experiment agree well with those of Holt and Marsham.[1] The exceptions to this agreement are distributions which show low-angle peaking in only one of the experiments. Two of these exceptions are the distributions for the reaction to the 1.278-Mev and 2.027-Mev levels in Si^{29}. The present experimental data for these cases are shown in Figs. 1 and 2. One can fit such a single-level distribution with the sum of two Butler curves calculated for orbital angular momentum transfer of $l=0$ and $l=2$, if both l values are allowed by angular momentum conservation.[6] Here, because the ground state of Si^{28} has spin and parity of 0^+, and the 1.28-Mev and 2.03-Mev states of Si^{29} have spin and parity of $\frac{3}{2}^+$ and $\frac{5}{2}^+$, respectively,[7] only $l=2$ is allowed. The 8-Mev data of Holt and Marsham show no low-angle peaking for these two states. Such "anomalous" behavior at low scattering angles as is exhibited in these distributions has been observed previously in (d,p) reactions,[8] and the extent of the "anomaly" seems to depend upon the incident energy of the deuterons.

One must of course consider the possibility that this unusual behavior results from an impurity in the target. In the present case, however, we believe that there is strong evidence that an impurity is not responsible, and that the forward rises in the two distributions are a property of the $Si^{28}(d,p)Si^{29}$ reaction to the 1.28-Mev and 2.03-Mev states, at the incident deuteron energy of 15 Mev.

The two other exceptions are the distributions for the Si^{29} 3.06-Mev and 3.62-Mev states, for which Holt and Marsham obtained low-angle rises. Each of their distributions was fitted by the sum of two Butler curves, one of which, viz., the $l=0$ curve, was assigned to the (d,p) reaction on either the Si^{29} or Si^{30} in the natural silica target.[1] In the present experiment, no low-angle peaking for the 3.06-Mev level distribution was observed down to $\theta_{c.m.} \approx 6°$. In addition, the enriched target data show that in this region of Q the $Si^{29}(d,p)$ and $Si^{30}(d,p)$ reactions do not produce any proton groups of magnitude sufficient to distort the Si^{29} 3.06-Mev level distribution at any forward scattering angle.

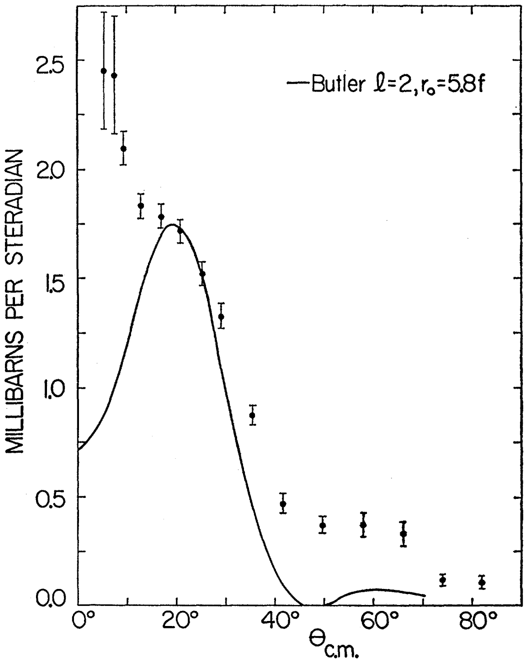

FIG. 2. Angular distribution of the $Si^{28}(d,p)Si^{29}$ 2.027-Mev state.

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[6] S. T. Butler and O. H. Hittmair, *Nuclear Stripping Reactions* (John Wiley & Sons, Inc., New York, 1957).

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[8] E. W. Hamburger and A. G. Blair, Phys. Rev. **119**, 777 (1960).

TABLE I. Summary of $Si^{28}(d,p)Si^{29}$ reaction data.

Si^{29} level (Mev)	l	r_0(f)	J^π	Θ^2, present experiment	Θ^2, H-M[a]
g.s.	0	6.0	$\frac{1}{2}+$	0.021	0.022
1.278	2	5.9	$\frac{3}{2}+$	0.014	0.019
2.027	2	5.8	$\frac{5}{2}+$	0.0034	0.005
2.424	Isotropic		$\frac{3}{2}+$	<0.0003	...
3.064	2	5.2	$\frac{3}{2}+$	0.0053	0.003
			$\frac{5}{2}+$	0.0036	0.002
3.620	3	5.6	$\frac{5}{2}-$	0.017	0.017
			$\frac{7}{2}-$	0.013	0.013
4.079	Isotropic			...	...
4.930	1	5.3	$\frac{1}{2}-$	0.065	0.058
			$\frac{3}{2}-$	0.032	0.029
5.937	2	5.8	$\frac{3}{2}+$	0.0015	*b*
			$\frac{5}{2}+$	0.0010	
6.189	3	6.2	$\frac{5}{2}-$	0.0071	*b*
			$\frac{7}{2}-$	0.0054	
6.380	1	5.2	$\frac{1}{2}-$	0.031	0.023
			$\frac{3}{2}-$	0.016	0.012

[a] The results in this column were obtained by Macfarlane and French (reference 11) from the data of Holt and Marsham (reference 1).
[b] Angular distributions to these levels were not obtained by Holt and Marsham (reference 1).

The angular distribution below $\theta_{c.m.}\approx 25°$ of the 3.62-Mev Si^{29} level could not be obtained in the present experiment owing to interference of the proton group from the $C^{12}(d,p)C^{13}$ ground-state reaction. One can, however, compare the present enriched-target data and the expected height of the *second* maximum of an $l=0$ distribution; from this comparison an upper limit of $\frac{1}{10}$ the cross section required by Holt and Marsham's data can be placed on an $l=0$ contribution from the $Si^{29}(d,p)Si^{30}$ or the $Si^{30}(d,p)Si^{31}$ reaction. We conclude that, if not produced as a result of a target impurity, the forward rises in the two distributions of Holt and Marsham must be due to a property of the $Si^{28}(d,p)Si^{29}$ reaction to the 3.06-Mev and 3.62-Mev states at the incident deuteron energy of 8 Mev.

No attempt at a theoretical interpretation of this low-angle peaking will be made here. In the cases just discussed, the phenomenon is dependent upon incident energy in a way which is not predicted by the simple plane-wave Born-approximation theory. A brief discussion of the matter can be found in reference 8.

Figures 3 and 4 show the angular distribution for protons from the 5.94-Mev and 6.19-Mev states of Si^{29}, fitted, respectively, by $l=2$ and $l=3$ Butler curves. The angular distributions of these two states were not obtained previously.

Table I lists the stripping parameters and reduced widths of all the Si^{29} level angular distributions obtained in the present experiment. The excitation energies of the levels are those given by White.[9] Proton groups from other known levels between 4.7 and 6.7 Mev of excitation were observed, but in general were weak and unresolvable. The values of l and r_0 listed were obtained from comparison of the measured angular distributions to curves calculated from the Butler formula.[6] From this comparison, also, the reduced widths Θ^2 of the transitions may be extracted. The values of Θ^2 obtained along with those obtained from the data of Holt and Marsham, who assign a $\pm 25\%$ error to their absolute cross-section scale, are shown in the final columns of Table I. The agreement between the two experiments is seen to be quite good in most cases, and in all cases is within the quoted errors.

The reduced width can be written as $\Theta^2(l)=\mathcal{S}\Theta_0^2(l)$, where the spectroscopic factor $\mathcal{S}$ is a measure of the overlap between the initial and final nuclear states, and $\Theta_0^2(l)$ is the single-particle reduced width.[10,11] From the agreement above one concludes either that the $2s$, $1d$, $2p$, and $1f$ single-particle reduced widths are approximately the same for deuteron energies of 8 and 15 Mev or, at the very least, if they are slightly different each is different by approximately the same fractional amount. These results are in agreement with those from stripping experiments on other isotopes.[11]

Because of its large separation from the 3.62-Mev level, the Si^{29} level at 6.19 Mev, reached by an $l=3$ transfer, in all probability has a spin of $\frac{5}{2}$. The 3.62-Mev level is undoubtedly a good $1f_{7/2}$ single-particle level,[11] which establishes a value of $\Theta_0^2(1f)\approx 0.013$ for this nucleus (see Table I). Other $\frac{5}{2}^-$ levels not more than 1 or 2 Mev above 6.19 Mev, having $\sum\Theta^2\approx 0.006$, should therefore be reached by the $Si^{28}(d,p)Si^{29}$ reaction; interfering C^{13} and O^{17} peaks make their detection difficult in the present experiment.

Because the Si^{29} level at 5.94 Mev is reached by an $l=2$ transfer, its spin and parity are either $\frac{3}{2}^+$ or $\frac{5}{2}^+$. The strong-coupling model,[12] using Nilsson wave functions,[13] when applied to the Si^{29} nucleus predicts a $\frac{3}{2}^+$

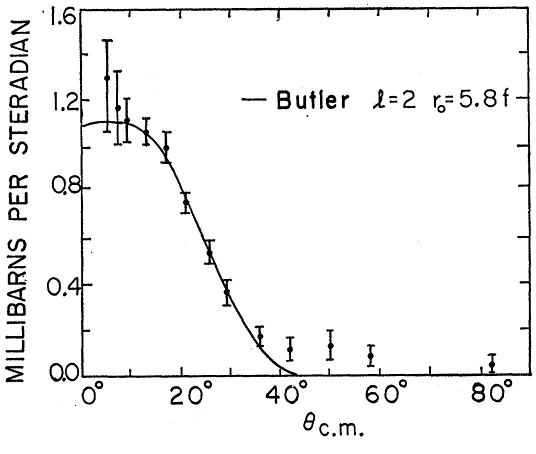

FIG. 3. Angular distribution of the $Si^{28}(d,p)Si^{29}$ 5.937-Mev state.

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[10] J. B. French, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960).

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[13] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 16 (1955); B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Skrifter **1**, No. 8 (1959).

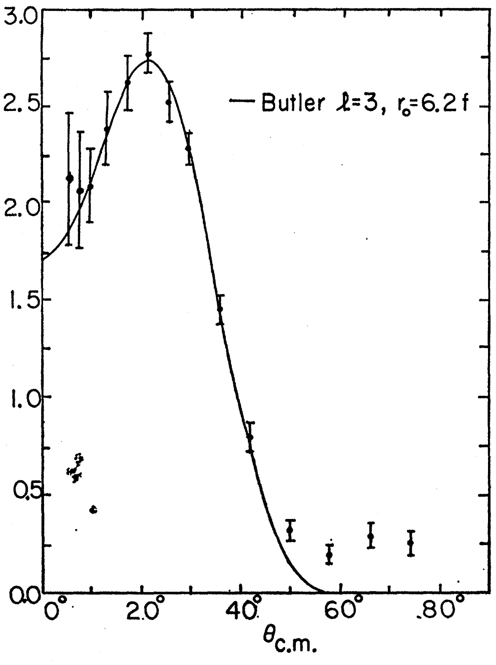

FIG. 4. Angular distribution of the $Si^{28}(d,p)Si^{29}$ 6.189-Mev state.

state in the neighborhood of 5 Mev. The predicted reduced width of the transition to this state is of the order of magnitude which is observed for the transition to the 5.94-Mev level. A $\frac{5}{2}^+$ state is also predicted a few Mev above the $\frac{3}{2}^+$ state, but the reduced width for the transition to this level would be vanishingly small, according to this model. Both of these predicted states arise from Nilsson orbits based on the $1d$-$2s$ shell. It is quite possible, however, that the 5.94-Mev level has a spin and parity of $\frac{5}{2}^+$ and is reached in the (d,p) reaction by a $2d_{\frac{5}{2}}$ transition. Other $\frac{5}{2}^+$ states with large $2d_{\frac{5}{2}}$ components should then lie within 1 or 2 Mev of this state. As noted above, these other states are essentially out of the range of the present experiment. No conclusion can be drawn regarding the spin of the 5.94-Mev level.

ACKNOWLEDGMENTS

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APPENDIX

A. Target Preparation

All targets used in the present experiment were made by evaporating SiO_2 powder onto a Mylar backing. In the vacuum evaporation technique the requirements of target uniformity are usually met by placing the source of the evaporant at a relatively large distance (10–20 cm) from a flat backing. The source is usually quite small, and every point on the surface of the backing material is at nearly the same distance from the source. The collection efficiency of this type of system is necessarily small, since the backing surface intercepts a small solid angle. In the present experiment, because a silicon thickness of a few tenths of a milligram per cm^2 was desired (in order to obtain relatively high count rates), and because SiO_2 enriched in Si^{29} or Si^{30} is quite expensive, a modification of the usual method was required.

Figure 5 shows a sketch of the evaporation apparatus used. Two pieces of brass tubing of slightly different diameters were cut and joined together so as to form the hollow semicylindrical shell shown in the figure. The inside section of tubing has a diameter of 2 cm; the length of the shell is 5 cm. Two holes were drilled through the outside section to provide for water cooling, as shown.

A filament cut from 10-mil tantalum sheet runs along the principal axis of the shell. The powdered silica was placed in small depressions in the filament, the ends of which were connected to a variable ac power source. Attached to the semicylindrical apparatus was a guide system (not shown) which served to position and hold the filament accurately as its temperature was raised during the evaporation process.

The approximate evaporation pattern of a system like that of Fig. 5 can be calculated for different numbers and locations of depressions in the filament and different amounts of the evaporant in each depression. In this manner the requirements for a uniform deposition over a given surface area can be determined. In the present case it was also possible to determine these requirements experimentally. The inside surface

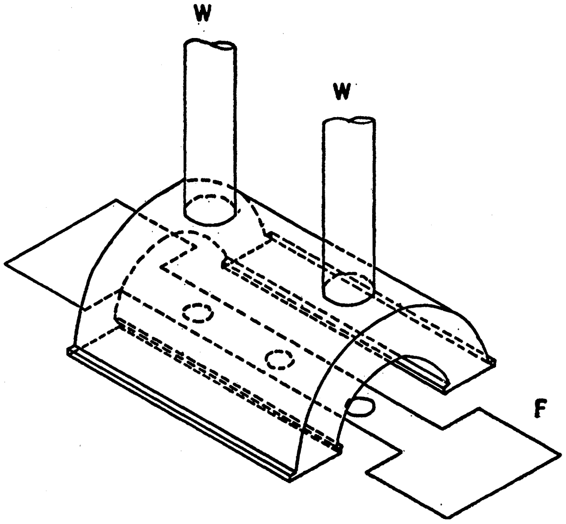

FIG. 5. Sketch of the evaporation apparatus used in the preparation of silicon targets. W is the water cooling line; F is a tantalum filament.

of the brass shell was polished, so that upon completion of an evaporation the deposited film could be illuminated by sodium light and reflection interference fringes observed. The conditions of evaporation could then be adjusted until the desired uniformity and target thickness were obtained. The system finally used consisted of three sources of evaporant spaced along the filament at 1-cm intervals, with 3.0 mg of SiO_2 in each of the end sources and 2.0 mg in the center. With this arrangement the deposited film was uniform within ±5% over an area of 1 cm by 2.5 cm. It should be noted that the film probably consisted mostly of SiO and Si, owing to the reduction of the SiO_2 by the tantalum.[14]

The deposited film could be removed only by being chipped or flaked from the brass surface; it could not be peeled. Several techniques were used in an attempt to obtain a self-supporting target, but each failed in some manner. The silicon targets finally used were backed with $\frac{1}{4}$-mil Mylar film.[15] The Mylar was first cemented to a piece of 1-mil Alcoa 2024 aluminum alloy[16] by a thin film of Araldite epoxy resin.[17] A thin coating of silicone grease was applied to the back surface of the aluminum in order to attain good thermal contact between it and the brass surface. This sandwich of films was fitted into the brass shell, where it was clamped into position. After the evaporation was completed, the Mylar film with its deposit of silicon oxide was peeled from the aluminum, coated (by evaporation) on each side with about 50 $\mu g/cm^2$ of silver (for its radiation and electrical conductivity properties), and mounted flat in a target frame.

Targets made in this manner had a tendency to pull in and wrinkle some around their edges when first put into the deuteron beam, but the portion of each target through which the beam actually passed always remained unwrinkled. Also, it was found that the sections of Mylar film had to be selected with some care, as a target would crack along a flaw in the Mylar after spending a few hours in the beam.

Several targets of naturally occurring and enriched silicon were made in this manner. Some have been exposed to the beam for thirty or forty hours; none has cracked or failed.

B. Absolute Cross Sections

The assignment of an absolute cross-section scale to the reaction data obtained in the present series of experiments would ordinarily have been made with the aid of a self-supporting natural silica target. With such a target one could compare at a chosen scattering angle the relative cross section of the $O^{16}(d,p)O^{17}$ ground-state reaction to that of a suitable silicon reaction. The absolute cross-section scale of the former reaction, for $E_d \approx 15$ Mev, is known from previous work at this laboratory. Owing to a cyclotron breakdown, however, these required data were not secured.

The method actually used is based on the geometry of the target evaporation system. Because (a) the dimensions of the system are accurately known, (b) the distribution pattern of the evaporated film was determined experimentally, and (c) a known amount of SiO_2 was evaporated in the preparation of each target, sufficient information is available to permit the computation of the areal density of the silicon in that portion of the target considered to be of uniform thickness. This method was used to determine the thickness of the natural silicon target and the result obtained is believed to be accurate within ±20%. From a knowledge of the solid angle intercepted by the detection system, determined in connection with the absolute cross-section measurement of the $O^{16}(d,p)O^{17}$ ground-state reaction, one can establish an absolute cross-section scale for the silicon reactions.

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[14] L. Holland, *Vacuum Deposition of Thin Films* (John Wiley & Sons, Inc., New York, 1956).

[15] Manufactured by E. I. duPont de Nemours and Company, Wilmington, Delaware.

[16] Manufactured by Aluminum Company of America, Pittsburgh, Pennsylvania.

[17] Manufactured by Ciba Products Corporation, Fair Lawn, New Jersey.