Differential Cross Sections of the $Li^6(N^{14},\alpha)O^{16}$ and $Li^7(N^{14},\alpha)O^{17}$ Reactions*†

JOHN W. WACHTER
University of Tennessee, Knoxville, Tennessee
and
Oak Ridge National Laboratory, Oak Ridge, Tennessee
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The angular distributions of α particles from the bombardment of Li^6 and Li^7 by 27.6-MeV incident nitrogen ions were measured from 0° to 135° c.m. Both α and recoil particles were detected in coincidence by silicon surface-barrier diodes. In the Li^6 measurements the O^{16} recoil was left in its ground state; Li^7 measurements did not resolve reactions leading to the ground state and to the 870-keV excited state of O^{17}. The Li^6 distribution exhibits a strong forward peak of approximately 75 μb/sr at 0° c.m., falling off, with some structure, to about 10 μb/sr at 90° c.m. at the backward angles, the cross section rises to a broad peak of 18 μb/sr at 112.5° c.m., falling to 9 μb/sr at 135° c.m. The Li^7 distribution is of similar shape at forward angles, falling from 140 to 30 μb/sr, but at backward angles rises to 84 μb/sr at 135° c.m. without clearly defined structure or symmetry with the cross section at forward angles. Calculation shows that the reactions do not proceed via a compound nucleus. The Li^6 reaction is treated as a deuteron transfer reaction using a modified tunneling theory and a distorted-wave calculation.

INTRODUCTION

HEAVY-ION reactions occurring at energies near the Coulomb barrier may proceed by two major reaction mechanisms: (1) by the formation of a compound nucleus and its subsequent de-excitation by the emission of particles, and (2) by a transfer reaction in which one or more particles are transferred from one nucleus to the other. Since the first identification of the transfer process by Reynolds, Scott, and Zucker,[1] and at about the same time, by Chackett *et al.*,[2] the neutron transfer reaction has been systematically studied by many investigators. A strong Q dependence and an angular distribution in which a single peak moves forward with increasing incident energy have been found to be a characteristic of all nucleon transfer processes near the Coulomb barrier. This is in contradistinction to an angular distribution symmetric about 90° characteristic of compound nuclear reactions.[3] Charged-particle transfer reactions at low Q values (<2 MeV) have been observed along with neutron transfer reactions by Newman and others[4,5] who find that these reactions conform to the general pattern exhibited by neutron transfers.

The present investigation is concerned with the reactions $Li^6(N^{14}, \alpha)O^{16}$ and $Li^7(N^{14}, \alpha)O^{17}$ in which the residual oxygen nuclei are left in their ground states. The interpretation of the lithium nuclei as loosely bound $\alpha-d$ and $\alpha-t$ structures suggests that these reactions would proceed as a deuteron and a triton transfer, respectively. The Q values are 19.3 MeV for the Li^6 reaction and 17.2 MeV for the Li^7 reaction and considerably exceed those of most transfer reactions which have been studied. The Li^6 reaction is of particular interest since the O^{16} product particle has its first excited level at 6 MeV above the ground state so that the ground-state reaction can be readily isolated experimentally.

EXPERIMENTAL

In the early work on transfer reactions, identification of the reaction products was accomplished by a radiochemical technique. Angular distributions were most often obtained using strips of aluminum foil placed around the target so as to catch the product nuclei ejected within specific ranges of polar angle. The excitation of the product nuclei in such cases is measured by range if at all. A means of measuring angular distribution pertaining to transitions leaving the product nuclei in specific states of excitation was described by Halbert and Zucker.[6] In this method, both product particles were detected and were counted in coincidence, thereby removing the ambiguity regarding the specific reaction. This method has been employed in the present investigation: both alpha and recoil oxygen particles were detected by silicon surface-barrier counters at the angles defined by the reaction kinematics, and only those alpha-particle pulses were accepted which coincided in time with a recoil-particle pulse having an amplitude corresponding to the energy of the recoil oxygen nucleus.

Figure 1 is a schematic diagram of the apparatus employed. Targets were prepared in the evaporation

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[1] H. L. Reynolds, D. W. Scott, and A. Zucker, Proc. Natl. Acad. Sci. U. S. **39**, 975 (1953).

[2] K. F. Chackett, J. H. Fremlin, and D. Walker, Phil. Mag. **45**, 173 (1954).

[3] M. L. Halbert, T. H. Handley, J. J. Pinajian, W. H. Webb, and A. Zucker, Phys. Rev. **106**, 251 (1957).

[4] E. Newman, Phys. Rev. **125**, 600 (1962).

[5] E. Newman, K. S. Toth, and A. Zucker, Phys. Rev. **132**, 1720 (1963).

[6] M. L. Halbert and A. Zucker, Phys. Rev. **115**, 1635 (1959).

chamber, shown at right, and were transferred into the beam position by means of the target-transfer rod. This rod was supported by an O-ring sliding seal at the evaporation chamber and carried at its end a screw used to pick up and secure the target. The entire apparatus was connected to the cyclotron vacuum system.

The N^{14} beam entered the scattering chamber vertically from below, passed through the target, and was collected in the Faraday cup. The beam current was monitored and integrated by means of a chopper amplifier. The targets were clipped to a holder which could be adjusted in angle and also shifted axially to bring either of two targets into the beam. Two movable arms carried the particle detectors and could be independently set at the appropriate angles for the alpha and recoil oxygen particles.

Typically, the acceptance angle for the alpha-particle counter was defined by a $\frac{1}{8}$-in.-diam aperture at 2.5 in. from the target, and that of the recoil counter by a $\frac{5}{16}$-in.-diam aperture at 4.25 in.

The particle detectors were *n*-type silicon surface-barrier counters. The sensitive depth of the counters was established from the proton and the deuteron cutoff energies, and was adjusted by changing the bias voltage so that the sensitive depth exceeded the range of the particle to be measured by 5 to 10%.

The alpha-particle detector was fabricated from 2200 Ω-cm silicon and was operated at a maximum bias of 300 V, corresponding to complete absorption of a 33-MeV alpha particle. Alpha particles of energy greater than 30 MeV were degraded in energy by means of Al absorbers so as to fall within the operating range of the counter. These absorbers were mounted in a remotely operated foil changer placed immediately in front of the detector collimator. The absorbing foil was chosen for each measurement so as to be at least thick enough to absorb completely N^{14} scattered elastically from the Ni target backing, and no thicker than necessary to degrade the alpha-particle energy sufficiently to bring it into the range of the detector.

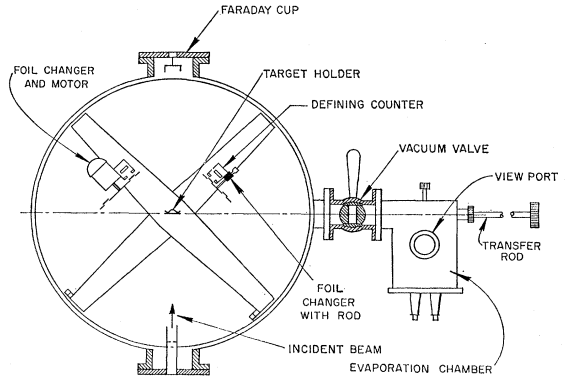

FIG. 1. Schematic drawing of the experimental apparatus.

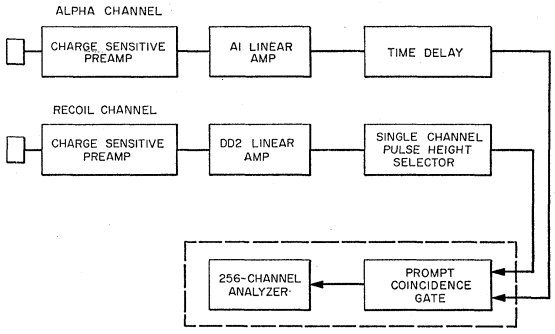

FIG. 2. Block diagram of the electronic equipment.

Figure 2 is a block diagram of the electronic apparatus. The surface-barrier counters were provided with separate regulated bias supplies with series resistors to protect against overload. Pulses from both channels were linearly preamplified and amplified. The recoil-particle pulse height was analyzed by a single-channel analyzer which developed a gating pulse if the pulse height lay between the appropriate limits for the recoil particle. This gating pulse was applied to the coincidence circuit of a multichannel analyzer allowing coincident alpha-particle pulses to be recorded. A variable time delay in the alpha-particle channel compensated for the time required to develop the recoil-channel gating pulse and was adjusted to bring simultaneous pulses at the detectors into coincidence at the multichannel analyzer.

Targets were prepared directly in the evaporation chamber. Metallic lithium which had been isotopically enriched to 95.6 w. % Li^6 or 99.3 w. % Li^7 was evaporated onto 2×10^{-6}-in.-thick nickel foil backings. A rotating cylindrical shutter protected both the interior of the scattering chamber and a plastic view port in the side of the evaporation chamber during target preparation.

To estimate the target thickness during the evaporation process, the target was transferred occasionally to the beam position and the beam energy loss measured. The target thickness was calculated from the energy loss assuming the ratio of stopping powers for nitrogen in lithium and nickel[7] equaled the ratio of stopping powers for protons of equal velocity in the same materials.[8] Evaporation was terminated when the target was about 1.5 MeV thick corresponding to 250 $\mu g/cm^2$ of lithium.

The thickness of the target as measured by beam-energy degradation was found to increase with target age after the first 8–12 h. This effect was ascribed to the accretion of contaminants on the target for the following reasons: (1) the alpha-particle reaction yields were

[7] H. L. Reynolds, D. W. Scott, and A. Zucker, Phys. Rev. **95**, 671 (1954).

[8] S. K. Allison and S. D. Warshaw, Rev. Mod. Phys. **25**, 779 (1953). See W. Whaling, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1958), Vol. 34, p. 193.

unaffected by the thickness increase, (2) yields of nitrogen elastically scattered from the lithium remained constant throughout the increase in thickness, and (3) measurements of nitrogen elastically scattered from oxygen showed a marked increase. The amount of lithium in a target was therefore measured on each freshly prepared target and assumed constant for the life of the target.

While measurements of the target thickness by beam degradation were useful for approximate estimates, impurities collected on the target during evaporation made this an unsatisfactory method for determining the exact amount of lithium on the target. Each target was therefore analyzed after bombardment by dissolving the lithium in 25 mg of dilute nitric acid and determining the total lithium using a spectrophotometric measurement of lithium concentration.

The recoil coincidence technique was employed for angular distribution measurements in the range from 75° to 135°. Ungated measurements were not feasible in this range because of the large background resulting from contaminants collected in the target by its gettering qualities. Coincidence gating based on recoil-angle selection discriminated against such competing reactions except for the $O^{16}(N^{14}, \alpha)Al^{26}$ reaction, for which the recoil angles are close to those of the lithium reactions. The lower energy of the Al^{26} recoil, compared with the oxygen recoil from the lithium reactions, permitted rejection of the unwanted alpha particles by pulse-height selection of the recoil gating pulse.

At angles below 75° the lower energy of the recoiling oxygen nucleus made its escape from the target increasingly less likely and more subject to large-angle deflection through multiple scattering. The correspondingly high energy of the alpha particle at these forward angles exceeded that of competing reactions, so that recoil coincidence was not required. At these forward angles the target was fixed normal to the beam and ungated measurements were made while the beam was monitored by the electronic charge deposited in the target. Measurements beyond 135° were not possible using recoil coincidence because the angular separation between the detector arms was limited to 120° by the equipment mounted on them so that the recoil counter was brought into the beam at backward angles. Data in this region were obtained by separate, ungated measurements.

In using the recoil coincidence method it was important that both detectors move in the same plane, also containing the incident beam. By taking beam spots on graph paper, and by means of recoil measurements of elastic scattering events on C targets it was concluded that the planes of motion of the two detectors had the required properties. Elastic scattering of N by C was used both to calibrate the angular scales of the detector arms, and to establish the correct timing of the electronic equipment. Measurements were not made on the lithium target unless the gated and ungated measurements on a 15–25 $\mu g/cm^2$ carbon target agreed to within 10%. The carbon measurement was required for this check since it was relatively free of background; similar measurements on the lithium targets yielded about a 30% difference between the gated and ungated measurements. The recoil counter solid angle was in all cases large enough to accept all oxygen atoms when alpha particles were detected in the defining counter. This was checked experimentally by varying collimator sizes.

To ascertain that the pulse-height selector permitted all recoil particles to be counted at all angles, the alpha-particle and recoil-detection channels were reversed at the detectors, so that the analyzer recorded the alpha-gated oxygen particles. The resulting energy spectrum was then used to set the width of the recoil pulse-height window for the following recoil-gated alpha-particle measurement.

Determinations of the lithium reaction yield at all angles were normalized to measurements taken at 75° where both gated and ungated measurements were repeated at frequent intervals. This angle was selected since, at greater angles, the increasing background hampered the ungated measurements, while at smaller angles the low energy of the recoil particle led to loss of coincidences through absorption and multiple scattering in the target. The yield of ungated particles at 75° was determined to $\pm 3\%$.

RESULTS

The angular distribution in the range from 0–135° was obtained from measurements on three Li^6 targets and two Li^7 targets. For each target, the yield at each angle of observation was divided by the average yield at 75° after correction for target angle and conversion of the counter solid angle to center-of-mass coordinates. The mean of these determinations over all targets gave the relative yield for that angle.

Figures 3 and 4 show the angular distributions for the Li^6 and Li^7 reactions. The error strikes apply to the angular distribution only and do not include the error in the absolute cross section. Errors were determined for angles from 0 to 135° by calculating the probable limits of error of the mean relative yield based upon the agreement among all relative yields at each angle.

The angular distribution was extended into the backward angles using measurements taken from a separate ungated angular distribution covering the range from 40 to 163°. The errors for data at angles beyond 135° were found from the mean of the percentage difference between the reported angular distribution and the extended angular distribution in the region where they overlapped. The assigned limits of error include the mean error of the reported distribution.

The determination of the absolute differential cross section at 75° was based on target thicknesses obtained

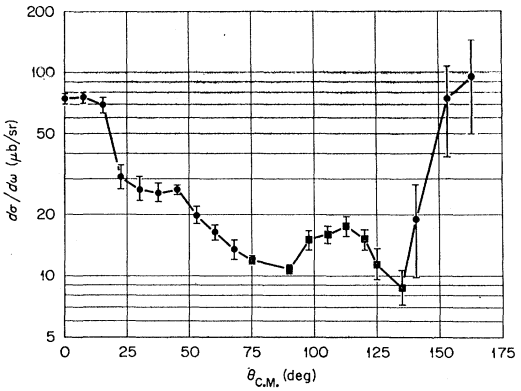

FIG. 3. Differential cross section of the $Li^6(N^{14}, \alpha)O^{16}$ reaction. Circles denote ungated measurements; squares denote recoil coincidence gated measurements. Limit strikes define the limits of error [LE(0.5)] of the angular distribution.

from the spectrophotometric determination of total lithium in the targets. To determine the number of N^{14} atoms hitting the target, the average charge of the nitrogen ions leaving the target had to be known. The energy of the beam entering the target was determined to be 26.7 MeV using the method described by Halbert and Zucker,[9] from which a mean beam energy of 25.9 MeV was inferred from the energy loss in the targets. Ions leaving the target had an energy of 25.05 MeV and an average charge of 6.0 e, based on the measurements of Reynolds, Scott, and Zucker.[7] Integrating over the angular distribution gave absolute total cross sections of 0.31 mb for the Li^6 reaction and 0.5 mb for the Li^7 reaction.

The primary source of error in the absolute cross section is that due to the measurement of target thickness. The determination of the lithium surface density at the beam spot from total lithium and area measurements is estimated to be accurate to $\pm 10\%$. The error in the determination of the integrated charge is probably about $\pm 8\%$, due primarily to the changing thickness of the target during bombardment. Uncertainties in the solid-angle determination are about $\pm 4\%$. The error on the total cross section is therefore estimated as $\pm 15\%$.

DISCUSSION

Of the two nuclear reaction mechanisms possible for these reactions, the shape of the angular distribution suggests a direct, rather than an evaporative reaction. Specifically, the broad peak in the backward direction of the Li^6 angular distribution makes it appear probable that a deuteron has been deposited in the N^{14}, and that the alpha particle has recoiled in the backward direction.

A compound nucleus reaction is energetically possible, however. For example, in the Li^6 reaction the center-of-mass energy is 8.01 MeV, compared to a Coulomb barrier of 4.77 MeV. Penetration of this barrier can occur with the formation of a Ne^{20} compound nucleus excited to 32 MeV. If the reaction seen in this experiment proceeded entirely in this fashion, the specific decay process is the evaporation of an alpha particle which carries away the total available energy and leaves the residual nucleus in its ground state.

The cross section for the ground-state transition of this reaction was estimated via the statistical model. Penetrabilities of Feshbach, Shapiro, and Weisskopf[10] were used to obtain a compound nucleus cross section of 0.585 b and the formulation of Lane and Lynn[11] to obtain a branching ratio of 0.47 for alpha-particle emission. The fraction of emitted alpha particles which leave the residual nucleus in the ground state was found by numerical integration of the relative intensity distribution as given by Blatt and Weisskopf.[12]

These calculations gave 4.3 μb as the cross section for the $Li^6(N^{14}, \alpha)O^{16}$ reaction if it proceeded entirely by the formation of a Ne^{20} compound nucleus and subsequent decay into an alpha particle and an O^{16} nucleus in its ground state. This cross section is about two orders of magnitude smaller than the measured cross section. Since this method of estimating cross section has been found to yield values which are within a factor of 5 of the experimental measurements,[13] it appears that the contribution to the measured cross section due to decay of the compound nucleus is not more than about 5%.

A similar conclusion was reached when the energy distribution of the alpha particles was compared with the energy spectrum predicted from the statistical model. The relative intensity distribution I_b of the outgoing alpha particles from a compound nucleus of

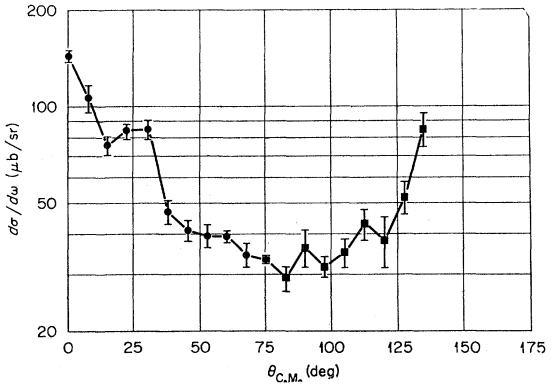

FIG. 4. Differential cross section of the $Li^7(N^{14}, \alpha)O^{17}$ reaction. The significance of the symbols is the same as for Fig. 3.

[9] M. L. Halbert and A. Zucker, Phys. Rev. **121**, 1190 (1961).

[10] H. Feshbach, M. M. Shapiro, and V. F. Weisskopf, Atomic Energy Commission Report, NYO 3077, 1953 (unpublished).

[11] A. M. Lane and J. E. Lynn, Nucl. Phys. **646** (1959).

[12] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), pp. 342–370.

[13] D. E. Fisher, A. Zucker, and A. Gropp, Phys. Rev. **113**, 542 (1959); J. J. Pinajian and M. L. Halbert, *ibid.* **113**, 589 (1959).

excitation energy is given approximately, and well enough for our purposes, by

$$I_b(\epsilon) \propto \epsilon\sigma_c \exp[b(\epsilon_{by}-\epsilon)^{1/2}]d\epsilon,$$

where the formula and notation are from Blatt and Weisskopf.[12] It follows that

$$\ln[I_b(\epsilon)/\epsilon\sigma_c] \text{ versus } (\epsilon_{by}-\epsilon)^{1/2}$$

is linear for an evaporative reaction. The measured energy distribution at 0 and 90° was plotted in this fashion using for σ_c the cross section for capture of an alpha particle by O^{16} given by Shapiro[14] and a maximum alpha-particle kinetic energy ϵ_{by} of 27.26 MeV. It was found that the spectra were made linear in the region of low-energy alpha particles, but that the ground-state peaks were about 50 times higher than the straight line extrapolation of this linear portion of the plotted curves.

The above computations, in conjunction with the asymmetric angular distributions, show that the measured cross sections result principally from the direct reaction processes of a deuteron transfer to the Li^6. Similar conclusions can be made for the triton transfer to the Li^7.

It is of interest to compare the experimental data with the predictions of the Breit-Ebel[15] nucleon tunneling theory even though it does not apply to charged-particle transfer reactions or to reactions having a high Q. The comparison was made for the Li^6 reaction which exhibits a pronounced backward peak and which involves only ground-state transitions.

Breit and Ebel assume Rutherford trajectories for the initial and final particles of the reaction and treat the motion of the transferred particle as a quantum mechanical tunneling event. They show that the angular distribution should have the form:

$$\frac{d\sigma}{d\Omega} \propto \frac{K^2}{\sin^3(\theta/2)} \exp\{-\alpha R_{\min}-\bar{\alpha}\bar{R}_{\min}\},$$

where $\alpha=[(2m/\hbar^2)S]^{1/2}$ for the transferred nucleon of mass m and separation energy S in the initial nucleus. Similarly, $\bar{\alpha}=[(2m/\hbar^2)\bar{S}]^{1/2}$, where $\bar{S}=S+Q$ is the separation energy of the transferred nucleon in the final nucleus. $R_{\min}$ is the minimum separation between Rutherford orbits for observed particle deflection angle θ and is related to the classical distance of closest approach R_0 by

$$R_{\min}=R_0[1-\csc(\theta/2)]; \; R_0=Z_1Z_2e^2/(2E_{c.m.}).$$

Although this distribution does not take into account competition with compound nucleus formation, and so does not reproduce the angular distribution, it has been found to give moderately good agreement in predicting the initial rise of the transfer peak. It is convenient to plot the experimental data as in Fig. 5, in the form

$$\ln\{K^{-2}\sin^3(\theta/2)(d\sigma/d\Omega)\} \text{ versus } R_{\min}$$

so as to facilitate the comparison with the theoretical slope defined by $\alpha R_{\min}-\bar{\alpha}\bar{R}_{\min}$. No agreement was found when S and $\bar{S}$ were taken as the nuclear binding energies in the Li^6 and O^{16}, respectively.

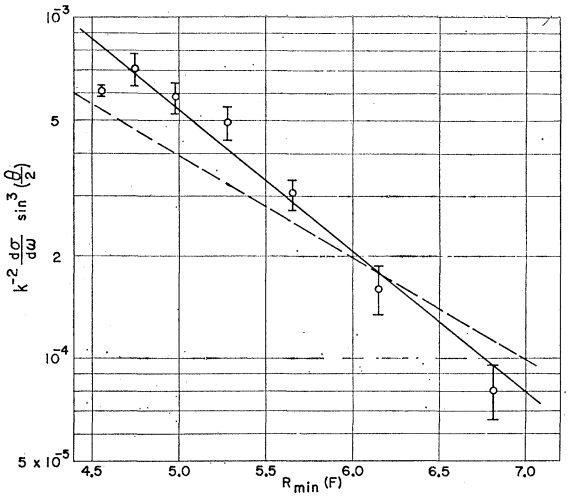

FIG. 5. The lithium-6 data plotted according to Breit and compared with the slope predicted by the tunneling theory where account has (solid line) and has not (dashed line) been taken of the Coulomb barriers in calculating the separation energies. $R_{\min}$ is defined in the text.

The tunneling theory was developed for neutron transfers and ignores the effect of the Coulomb field on the transferring particle. In order to take partial account of this effect, it was assumed that the separation energies were made up of a nuclear part S_ν and a Coulomb part S_c, so that $S=S_\nu+S_c$. S_ν was taken as the nuclear binding energy of the deuteron in the Li^6 (1.47 MeV), and S_c as the corresponding Coulomb barrier in the d-α system: $S_c=Z_\alpha Z_{\text{deut.}}e^2/r_\alpha=2.40$ MeV. We use $r_\alpha=1.2$ F, which is a common value for the alpha-particle radius.

The comparison between the experimental data and the normalized theoretical slope derived in this fashion is also shown in Fig. 5.

Three factors combine to render the present tunneling theory unsuitable for these data: (1) the theory neglects the effect of the Q value, whereas both reactions have energy releases in excess of 16 MeV, (2) the theory only considers transfer of a neutral particle, whereas these reactions are charged-particle transfers, and (3) the theory applies only below the Coulomb barrier, whereas here $E/E_b=1.67$. In view of these important departures from the conditions of validity of the theory, it is interesting that so good a fit can result from a reasonable choice of parameters.

[14] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).
[15] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1950); **104**, 1030 (1956).

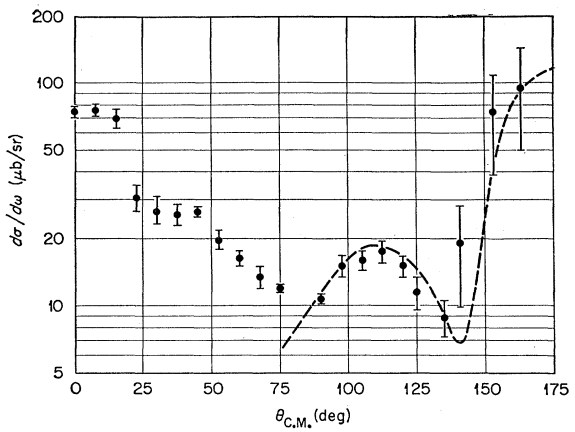

FIG. 6. Comparison of the measured $Li^6(N^{14}, \alpha)O^{16}$ angular distribution with the normalized stripping reaction calculation of the Bassel-Drisko-Satchler distorted-wave Born approximation (DWBA).

The heavy-ion transfer process is similar in some respects to (d,p) stripping. Advantage was therefore taken of the availability to the author of the Bassel-Drisko-Satchler distorted-wave code "SALLY," written for the IBM 7090.[16] This machine program derives wave functions for the stripping process from the distorted waves computed from the optical-model potentials for the elastic scattering. The zero range approximation is made, and the wave functions for the transferred particle bound to incident and product particles are approximated by harmonic oscillator functions. Since no N-Li scattering data exist the optical-model potentials used in the calculations were those found to fit N-Be elastic scattering data: $V=45.57$ MeV, $W=13.8$ MeV, $R_0=1.7$ F, and $R_c=1.4$ F.

The calculated transfer cross section is shown in Fig. 6 and agrees reasonably well with the experimental cross section over the range of angles of the transfer peak. An attempt was made to fit the forward angle cross sections assuming that a knock-on process took place. This calculation, also done by the "SALLY" code, yielded a poor fit, as an independent calculation, when the N-Be optical potentials were used. If it was assumed that the full distribution represented the coherent mixing of the two processes, stripping and knock-on, it was found that the original agreement with the transfer peak was destroyed.

The $Li^7(N^{14}, \alpha)O^{17}$ reaction data are even more difficult to analyze since both the ground state and the first excited state transitions are included in the cross section. Therefore, no attempt was made to analyze this reaction either by applying the tunneling or distorted wave formalisms.

[16] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Atomic Energy Commission Report ORNL-3240, 1962 (unpublished).

ACKNOWLEDGMENTS

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