Energy Dependence of Elastic and Inelastic Scattering of Alpha Particles by C^{12} and the $C^{12}(\alpha,p)N^{15}$ Reaction*

R. A. ATNEOSEN,† H. L. WILSON, M. B. SAMPSON, AND D. W. MILLER
Physics Department, Indiana University, Bloomington, Indiana
(Received 27 March 1964)

Angular distributions of alpha groups corresponding to elastic scattering and inelastic excitation of C^{12} to 4.43 MeV and of the proton group leading to the ground state of N^{15} have been measured at eight different energies between 20 and 23 MeV. The angular distributions show major changes over 400-keV energy intervals similar to those observed at higher and lower energies for the same scattering processes. The backward peaking in the $C^{12}(\alpha, p)N^{15}$ reaction is not maintained over the energy region 22 to 25 MeV, as previously thought, but decreases again at energies slightly greater than 22 MeV.

I. INTRODUCTION

NUMEROUS experiments have been performed since 1950 in which angular distributions for groups corresponding to elastic and inelastic scattering as well as reaction products have been obtained for alpha particles incident on a wide variety of nuclei at incident energies up to 50 MeV. Experiments on the elastic scattering of alpha particles and some elastic-scattering theories have been reviewed recently by Eisberg and Porter.[1]

Certain direct-reaction models have been successful in integrating parts of the existing data on elastic scattering into a semiquantitative description of the interaction of alpha particles with nuclei. The first of these, the "APB model," was developed by Blair[2] on the basis of an earlier model proposed by Akhieser and Pomeranchuk.[3] The APB model attempts to explain the observed deficiency of alpha particles elastically scattered from heavy nuclei at large angles by assuming that all the partial waves in the incident beam with orbital quantum numbers less than some critical value are completely absorbed while the rest merely undergo a Coulomb phase shift. The main defects of the APB model, viz., the prediction of unobserved oscillations and excessive scattering at the extreme back angles, were removed in the "APBM model" with the introduction by McIntyre, *et al.*[4] of a smooth semiempirical variation of the scattering amplitudes from no absorption to total absorption over a small range in ℓ values. In the region of partial absorption, it was also necessary to introduce nuclear phase shifts with a similar smoothing. The APBM model has been quite successful in explaining the observed angular distributions of the elastic scattering of alpha particles by heavy nuclei. A similar approach by Igo and Thaler,[5] using an optical potential with volume absorption, was fairly successful in fitting elastic alpha-particle scattering from both light and heavy nuclei. An interesting feature of these fits is that elastically scattered alpha particles are essentially insensitive to the details of the nuclear interior, and that only the surface region is effective in returning alpha particles to the elastic channel, in agreement with the basic concepts of the APBM model. Recently, more sophisticated forms[6–10] of the optical model have been used for the theoretical analysis of elastic alpha-particle scattering.

The first direct-reaction theories of inelastic alpha-particle scattering assumed the incoming and outgoing alpha particles could be described by plane waves, in contradiction to the basic assumptions that are successful in explaining the elastic alpha-particle angular distributions. For nuclei with low-lying levels which are described as excitations of collective modes of nuclear motion, Blair[11] has extended a model introduced by Drozdov[12] and Inopin[13] to describe inelastic alpha-particle scattering with strong absorption of the alpha particles. Basically a diffraction scattering model in which the nuclear surface is specified by collective surface deformation parameters, this description involves very few free parameters and yields a simple relationship between the phases of the elastic and inelastic angular distributions. Considerable success has been attained with this model in fitting angular distributions for both elastic and inelastic scattering of alpha particles from nuclei with single-phonon collective modes of

* Supported by the U. S. Office of Naval Research and the National Science Foundation.
† Present address: Princeton University, Princeton, New Jersey.
[1] R. M. Eisberg and C. E. Porter, Rev. Mod. Phys. **33**, 190 (1961).
[2] J. S. Blair, Phys. Rev. **95**, 1218 (1954).
[3] A. Akhieser and I. Pomeranchuk, J. Phys. (USSR) **9**, 471 (1945).
[4] J. A. McIntyre, K. H. Wang, and L. C. Becker, Phys. Rev. **117**, 1337 (1960).
[5] G. Igo, and R. M. Thaler, Phys. Rev. **106**, 126 (1957).
[6] W. W. Eidson and J. G. Cramer, Jr., Bull. Am. Phys. Soc. **8**, 317 (1963).
[7] C. R. Gruhn, N. S. Wall, A. Bernstein, N. Baron, J. Need, and J. Vincent, Bull. Am. Phys. Soc. **8**, 358 (1963) and (private communication).
[8] H. F. Lutz, S. F. Eccles, and J. B. Mason, Bull. Am. Phys. Soc. **8**, 318 (1963).
[9] G. M. Temmer and H. R. Blieden, Bull. Am. Phys. Soc. **7**, 435 (1962).
[10] P. B. Weiss and R. H. Davis, Bull. Am. Phys. Soc. **8**, 47 (1963).
[11] J. S. Blair, Phys. Rev. **115**, 928 (1959).
[12] S. I. Drozdov, Zh. Eksperim. i Teor. Fiz. **28**, 736 (1955) [English transl.: Soviet Phys—JETP **1**, 588, 591 (1955)].
[13] E. V. Inopin, Zh. Eksperim. i Teor Fiz. **31**, 901 (1956) [English transl.: Soviet Phys.—JETP **4**, 764 (1957)].

excitation over a wide energy range.[14,15] However, it has not been successful in explaining the scattering of lower energy alpha particles by very light nuclei, in particular C^{12}. A model for both elastic and inelastic scattering in which the absorption is explicitly taken into account was recently introduced by Buck.[16] In this theory, the optical model is extended to include inelastic scattering from an even-even nucleus with a 0^+ ground state and a first excited 2^+ level. In the resulting coupled differential equations, the elastic and inelastic scattering are coupled through the off-diagonal terms of the potential, and the coupling with all excited states higher than the first is neglected. Buck has had considerable success in fitting the angular distributions for elastic and inelastic scattering of protons from nuclei exhibiting collective motions, e.g., Zn, Cr, Fe, and Ni.

The satisfactory explanation of the gross features of elastic alpha-particle scattering from heavy nuclei and the development of Blair's theory of inelastic diffraction scattering provided incentives for the experimental study of elastic and inelastic scattering of alpha particles by light and intermediate nuclei. In particular, the scattering of alpha particles by C^{12} has been studied rather extensively at energies in the range from 10 to 50 MeV. Prior to this experiment, angular distributions for elastic scattering had been obtained at numerous energies between 9.5 and 48 MeV.[5,17–28] Corresponding angular distributions had been measured for inelastic scattering to the first excited state of C^{12} (4.43 MeV) in all cases[29] except one.[26] Elastic and inelastic excitation functions had also been measured over various energy ranges from 10 to 30 MeV.[17,29–31]

Considerable attention has also been paid to the $C^{12}(\alpha,p)N^{15}$ ground-state reaction. This reaction should aid in determining the reaction mechanism operative in the interaction of alpha particles with C^{12} over the above energy range. Prior to this experiment, angular distributions of the proton group leading to the ground state of N^{15} had been measured at several energies in the range from 11 to 42 MeV.[17,32–37] Excitation functions had been measured from 9.5 to 19 MeV.[17,32]

In the above experiments, the angular distributions for scattered and reaction particles exhibit many of the features usually attributed to a direct reaction, viz., sharp oscillations, forward peaking, and apparent agreement with the Blair phase rule.[11] However, the distributions also show an unexpected energy dependence and, quite often, an unusual amount of backward peaking. The rapid energy variations in the elastic and inelastic scattering of alpha particles by C^{12}, particularly in the energy range near 22 MeV, were first demonstrated some years ago in the work of Rasmussen, Miller, and Sampson[30] at Indiana University. In an attempt to measure the angular distributions of scattered alpha particles incident at an energy of 22 MeV, it was found that the data were not reproducible from one day to the next which indicated that the cross sections were quite sensitive to day-to-day variations of the beam energy. Consequently, thick-target 90-deg laboratory excitation functions were measured for elastic and inelastic ($Q=-4.43$ MeV) scattering of alpha particles at bombarding energies from 20.4 to 22.6 MeV. The 90-deg differential cross sections were found to vary much more rapidly with energy than would be expected from simple direct-reaction theories. A tentative explanation put forth by the above authors for the observed "resonance" in the inelastic scattering was based on the formation of an intermediate state in O^{16} at an excitation energy near 23.5 MeV. In fact, it was later pointed out by Wall[38] that the calculations of Brown, Castillejo, and Evans,[39] which are based on a particle-hole interaction, predict the existence of excited levels of O^{16} at energies of approximately 22 and 25 MeV.

The advent of solid-state counters and multichannel analyzers makes feasible the measurement of angular distributions which change fairly rapidly with energy, since entire angular distributions can be measured over a short period of time during which the cyclotron beam

[14] D. K. McDaniels, J. S. Blair, S. W. Chen, and G. W. Farwell, Nucl. Phys. **17**, 614 (1960).
[15] J. S. Blair, G. W. Farwell, and D. K. McDaniels, Nucl. Phys. **17**, 641 (1960).
[16] B. Buck, Phys. Rev. **130**, 712 (1962).
[17] E. B. Carter, Ph.D thesis, Florida State University, 1962 (unpublished).
[18] J. S. Corelli, E. Bleuler, and D. J. Tendam, Phys. Rev. **116**, 1184 (1959).
[19] W. W. Eidson, Ph.D. thesis, Indiana University, 1961 (unpublished).
[20] C. Hu, S. Kato, Y. Oda, and M. Takeda, J. Phys. Soc. Japan **14**, 549 (1959).
[21] T. Mikumo, H. Yamaguchi, I. Nonaka, M. Odera, Y. Hashimoto, M. Kondo, and T. Maki, J. Phys. Soc. Japan **15**, 1158 (1960).
[22] T. Mikumo, J. Phys. Soc. Japan **16**, 1066 (1961).
[23] H. J. Watters, Phys. Rev. **103**, 1763 (1956).
[24] I. J. Van Heerden and D. J. Prowse, Nucl. Phys. **15**, 356 (1960).
[25] J. Aguilar, W. E. Burcham, J. Català, J. B. A. England, J. S. C. McKee, and J. Rotblatt, Proc. Roy. Soc. (London) **A254**, 395 (1960).
[26] G. Igo, H. E. Wegner, and R. M. Eisberg, Phys. Rev. **101**, 1508 (1956).
[27] A. I. Yavin and G. W. Farwell, Nucl. Phys. **12**, 1 (1959).
[28] F. J. Vaughn, University of California Radiation Laboratory Report No. UCRL 3174, 1955 (unpublished).
[29] G. E. Mitchell, E. B. Carter, and R. H. Davis (private communication).
[30] V. K. Rasmussen, D. W. Miller, and M. B. Sampson, Phys. Rev. **100**, 181 (1955).
[31] H. F. Lutz, J. B. Mason, and C. T. Paulson, Nucl. Phys. **43**, 405 (1963).

[32] J. R. Priest, D. J. Tendam, and E. Bleuler, Phys. Rev. **119**, 1295 (1960).
[33] M. Kondo, T. Yamazaki, and S. Yamabe, J. Phys. Soc. Japan **16**, 1091 (1961).
[34] I. Nonaka, H. Yamaguchi, T. Mikumo, I. Umeda, T. Tabata, and S. Hitaka, J. Phys. Soc. Japan **14**, 1260 (1959).
[35] C. E. Hunting and N. S. Wall, Bull. Am. Phys. Soc. **2**, 181 (1957).
[36] R. Sherr and M. Rickey, Bull. Am. Phys. Soc. **2**, 29 (1957).
[37] A. J. Lieber, F. H. Schmidt, and J. B. Gerhart, Phys. Rev. **126**, 1496 (1962).
[38] N. S. Wall (private communication).
[39] G. E. Brown, L. Castillejo, and J. A. Evans, Nucl. Phys, **22**, 1 (1961).

energy can be held fairly constant. The present work extends the previous study of the behavior of the C^{12} excitation functions[30] by obtaining angular distributions for groups corresponding to elastic scattering and inelastic excitation of C^{12} to 4.43 MeV for alpha particles incident at eight different energies in the range from 20.16 to 22.73 MeV. In agreement with Rasmussen *et al.*, major changes are often seen in the angular distributions over energy intervals of 300 keV; as yet, no interpretation has been found which correlates these changes. As a possible aid in narrowing down the reaction mechanisms and because of the rapid variations with energy seen in the work of Kondo *et al.*,[33] angular distributions have also been obtained for the proton group corresponding to the $C^{12}(\alpha,p)N^{15}$ reaction leading to the ground state of N^{15} at eight different energies from 20.17 to 22.81 MeV.

Recent independent measurements have been made of the elastic scattering at five different energies from 21.2 to 22.7 MeV by Jodogne *et al.*,[40] and of the (α,p) reaction at seven different energies from 19.7 to 22.0 MeV by Yamazaki *et al.*[41] However, the data presented here have the advantage of including not only the inelastic scattering, but of being taken under almost identical experimental conditions, so that cross sections, energies, etc., can be compared with far more accuracy than would be possible for measurements made independently at different laboratories.

II. EXPERIMENTAL TECHNIQUES

The alpha-particle beam from the Indiana University cyclotron is collimated, focused, deflected by an analyzing magnet, and collimated again before entering a 16-in.-diam scattering chamber. Scattered particles or reaction products from a carbon target at the center of the chamber were detected with a solid-state counter[42] mounted in the rotating lid of the chamber or with a point-focusing 180° heavy-particle magnetic spectrometer attached to the chamber. Details of this spectrometer have been described elsewhere.[30]

The energy of the incident alpha-particle beam was determined by observing alpha particles elastically scattered by carbon at 90° in the laboratory with the magnetic spectrometer. The particle group measured with the spectrometer had a fairly broad energy distribution resulting from the finite beam spread and large entrance angle of the spectrometer. Once the beam energy had been determined by traversing the elastic peak with the spectrometer, it was monitored during the angular distribution measurements by setting the spectrometer field at a fixed value corresponding to one-half of the counting rate measured on the peak of the initial curve. A change in the mean beam energy produced a shift in the curve and consequently a change in the counting rate at the fixed value of the field. However, account had to be taken of the energy dependence of the cross section in performing these monitor measurements to prevent accidental cancellation between these two effects. For a given angular setting of the solid-state counter, the counts accrued at the monitor field during the period of integration of the beam charge were plotted to give a check on the constancy of the energy. Variations in the average beam energy, which were much more rapid than the normal period of integration (5 to 20 min), therefore appear as a part of the beam-energy resolution.

Control of the energy of the alpha particles incident on the target was accomplished either with the use of energy degradation foils preceding the first beam collimator or by altering the cyclotron operating frequency. The latter method was found to be superior, not only in maintaining beam quality but also in convenience. Small energy changes were attained by varying the interelectrode capacitance of the internal elements of the cyclotron ("dees," deflector, etc.) through a rearrangement of their relative positions. Major changes were produced by the introduction of a 5-in. by 20-in. water-cooled plate inside one of the torpedo tubes with the long edge of the plate parallel to the "dee" line. By careful adjustment of the spacing between this plate and the "dee" line, the cyclotron beam energy could be selected without undue difficulty.

At the conclusion of the experiment, the availability of a good-resolution (0.35% at 8.78 MeV) ORTEC surface-barrier detector and a Nuclear Data 1024-channel analyzer made a measurement of the energy distribution of the particles in the beam possible. The measurement was accomplished by observing alpha particles scattered elastically at 90° in the laboratory from a thin gold foil (26 keV thick for 8.78-MeV alpha particles) using a 1° acceptance collimator in front of the ORTEC detector. On combining the measured beam spread with the contribution due to the measured thickness of the carbon target, it was concluded that the total spread in energy of the alpha particles incident on the carbon nuclei during the main experiments had been variable but under the worst conditions was about 350 keV,[43] usually at the lowest energies. This resolution would appear to compare very poorly with a tandem Van de Graaff operating at 20 MeV. However, the lower intensity alpha-particle beam obtained in published tandem experiments required the use of fairly thick targets for good counting statistics and resulted in a resolution on the order of 100 keV, only a factor of 3 or so better than the present experiment.

The natural carbon target used in this experiment

[40] J. C. Jodogne, P. C. Macq, and J. Steyaert, Phys. Letters **2**, 325 (1962).

[41] T. Yamazaki, M. Kondo, and S. Yambe, J. Phys. Soc. Japan **18**, 620 (1963), and private communication.

[42] Purchased from Hughes Research Laboratories, Malibu, California.

[43] Subsequent measurements have shown that the method described can be used to guide the adjustment of cyclotron parameters for optimum resolution, which may be maintained at 150 keV.

was prepared from a colloidal graphite suspension in isopropyl alcohol.[44] A clean microscope slide was introduced momentarily into this suspension diluted with acetone and allowed to dry in a horizontal position. The film was then peeled from the slide and mounted on a target frame. The target was subsequently baked for several hours under a heat lamp to remove volatile components. Analysis of the alpha particles scattered by this target showed only oxygen and hydrogen contaminants in any appreciable amount. An upper limit of 10% was estimated for the oxygen content of the target.

The target thickness was measured by observing the energy loss of ThC' alpha particles from a ThB source on passing through the target. Although the same target was used throughout the entire experiment, various factors such as pump-oil deposition, contraction due to beam heating, etc., contributed to a change in the target thickness. The thickness was measured to be 320 and 340 μg/cm^2 for the elastic-inelastic and (α,p) angular distributions, respectively, with an uncertainty in the relative thickness of 10% over the period during which each set of data was accumulated.

The angular distributions for alpha-particle groups corresponding to elastic scattering and inelastic excitation to the 4.43-MeV level of carbon were observed with a Hughes diffused-junction (p-n) solid-state detector. The protons from the (α,p) reaction leading to the ground state of N^{15} were detected with a lithium-drifted (p-i-n) solid-state detector. Signals from the solid-state detector were initially amplified by a high-gain, low-noise Tennelec Model-100A preamplifier

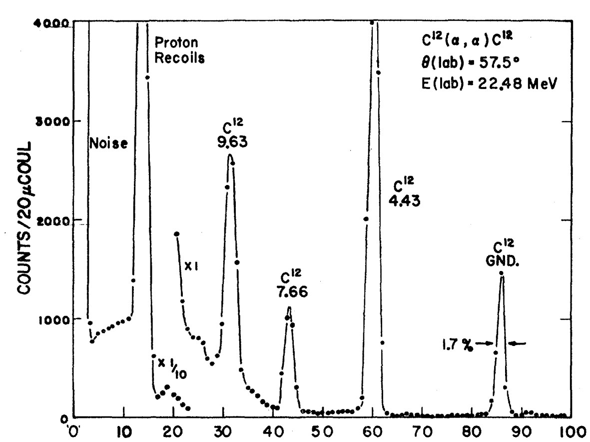

FIG. 1. Spectrum from the Hughes detector at a lab angle of 57.5° for 22.48-MeV alpha particles incident on carbon using a $\frac{1}{16}$-in. by $\frac{1}{4}$-in. collimator (0.0066% of the total sphere). The energy resolution is due to contributions from the incident beam, detection system, and finite acceptance angle. The peak at channel 86 was identified as elastic scattering, while the other three peaks correspond to inelastic scattering leading to the first three excited states of C^{12}.

[44] Sold commercially by Acheson Colloids Corporation under the trade name of Dag Suspension No. 154.

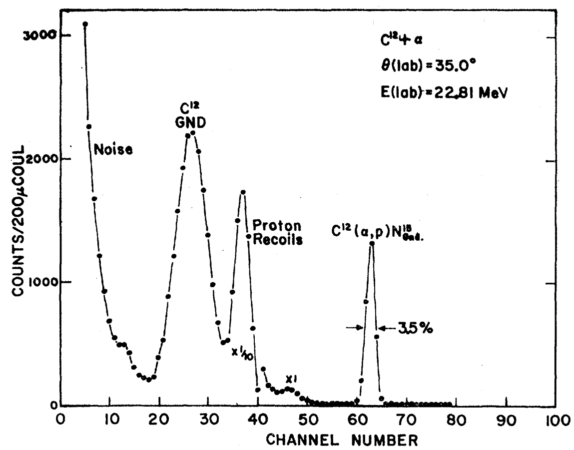

FIG. 2. Spectrum from the lithium-drifted detector at a lab angle of 35.0° for 22.81-MeV alpha particles incident on carbon using a $\frac{1}{16}$-in.-diam collimator (0.0017% of the total sphere). The increase in the width of the peak compared to that in Fig. 1 is primarily due to the difference in detectors. The peak near channel 27 was identified as being due to elastic scattering. The two other prominent groups were identified to be the proton group leading to the ground state of N^{15} and the recoil-proton group.

which was coupled directly to the counter holder for best resolution. A Tennelec Model-900 RM power-supply provided the preamplifier power as well as a choice of external or internal bias voltage for the counters. The pulses were amplified and sorted by a Radiation Instruments Development Laboratory Model A-261 amplifier and 100-channel pulse-height analyzer. Typical pulse-height spectra from the Hughes and lithium-drifted detectors are shown in Figs. 1 and 2, respectively. The conspicuous difference between these spectra, which provided a means of particle identification, was a consequence of the difference in the surface dead layers and depletion depths of the two detectors. The Hughes detector had a depletion depth which would stop 22-MeV alpha particles but cause protons to lose a maximum energy of about 6 MeV in the sensitive region of the detector. By comparison, the dead layer on the front surface was negligible. In contrast, although the lithium-drifted detector was capable of stopping at least 15-MeV protons, the dead layer on its surface was so thick that elastically scattered alpha particles lost most of their energy there and very little in the sensitive region.

The solid angle for the scattered particles was defined by a collimator preceding the solid-state detector. This collimator was located at a distance of 4 in. from the beam spot which was normally $\frac{1}{8}$ in. by $\frac{1}{8}$ in. in size. Through an external arrangement, the choice of a $\frac{1}{16}$-in.-diam hole, a $\frac{1}{16}$-in. by $\frac{1}{4}$-in. slit, or a $\frac{3}{16}$-in. by $\frac{1}{4}$-in. slit could be made. Good agreement was obtained between several independent measurements of the ratios of the corresponding solid angles. The distance between the detector aperture and the beam spot was constant to within $\frac{1}{32}$ in. for all angular positions of the solid-state counter (representing a 1.5% variation in

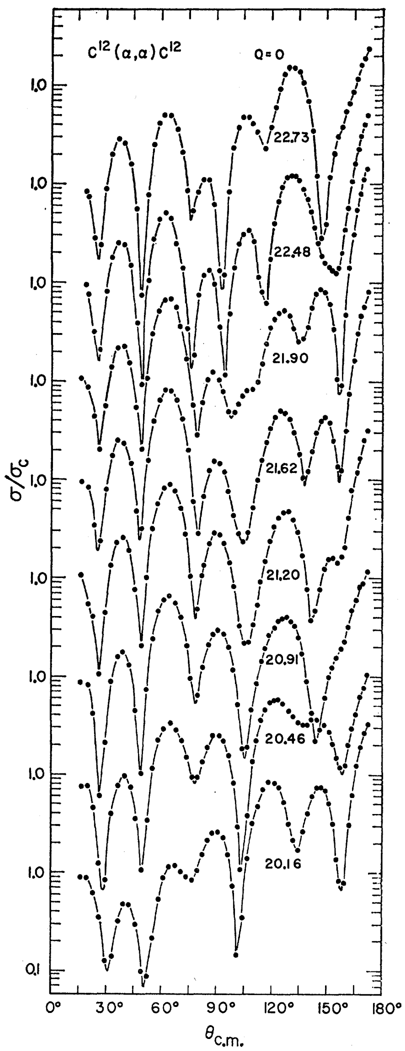

FIG. 3. Energy dependence of the $C^{12}(\alpha,\alpha)C^{12}$ angular distribution plotted as the ratio to the Coulomb differential cross section on a logarithmic scale. The angular range is from about 16° to 172° c.m. Statistical counting errors are less than 2% and the background subtraction errors are negligible except at angles less than 40° c.m., where oxygen contamination and slit scattering combine to increase the relative error to 17%.

the solid angle). The zero angle was determined from partial angular distributions for elastic scattering measured on each side of the beam. A comparison of the cross sections on each side showed that the left-right asymmetry was usually less than 1.0%.

TABLE I. The average interaction energies and errors for the elastic-inelastic angular distributions. All the energies were obtained with various combinations of foils except for the runs at 22.73, 22.48, and 20.91 MeV which were obtained by varying the cyclotron operating frequency. An adequate monitor was not obtained for the runs at 22.48, 21.20, 20.46, and 20.16 MeV as is indicated by the increased values of the relative errors.

Transmission angular distribution (MeV)	Reflection angular distribution (MeV)	Complete angular distribution (MeV)	Relative error (MeV)	Absolute error (MeV)
22.74	22.72	22.73	0.06	0.13
22.48	22.47	22.48	0.08	0.14
21.90	21.89	21.90	0.05	0.12
21.61	21.62	21.62	0.04	0.12
21.20	21.20	21.20	0.06	0.14
20.90	20.92	20.91	0.06	0.13
20.48	20.44	20.46	0.08	0.14
20.10	20.22	20.16	0.10	0.16

TABLE II. The average interaction energies and errors for the (α,p) reaction angular distributions. The smaller errors here as compared to Table I are the result of improved experimental technique in obtaining and monitoring the energies. All energies were obtained without foils and were properly monitored.

Transmission angular distribution (MeV)	Reflection angular distribution (MeV)	Complete angular distribution (MeV)	Relative error (MeV)	Absolute error (MeV)
22.81	22.81	22.81	0.04	0.12
22.50	22.50	22.50	0.04	0.12
21.90	21.89	21.90	0.04	0.12
21.64	21.64	21.64	0.04	0.12
21.20	21.20	21.20	0.04	0.12
20.92	20.90	20.91	0.04	0.12
20.46	20.43	20.44	0.05	0.12
20.17	20.16	20.17	0.04	0.12

III. RESULTS

Each angular distribution presented here is composed of two parts corresponding to the orientation of the target with respect to the incident beam, 45° in transmission or 45° in reflection. This division roughly corresponds to scattering angles less than or greater than 90°, respectively. For each angular position of the solid-state detector, the average energy of interaction of the incident alpha particles with the C^{12} nuclei during that period of data accumulation (taken here as the average energy of the incident alpha particles at the center of the target) could be calculated from the counts observed with the spectrometer at the monitor value of the field. This calculation was based on the spectrometer curves obtained before or after that particular part of the angular distribution was measured. The energies so obtained were averaged individually for the transmission and reflection portions of the angular distributions, which were not necessarily measured on the same day, and these two energies were in turn averaged to yield an energy with which the entire angular distribution could be labeled. The results of these measurements, together with the relative and absolute errors in the energies characterizing the complete angular distributions, are presented individually for the elastic-inelastic and (α,p) angular distributions in Tables I and II, respectively.

In addition to the usual uncertainties in the energy measurements, the errors include energy fluctuations observed with the spectrometer as well as the ability to match the energies of the transmission and reflection portions of the elastic-inelastic angular distributions which were obtained on consecutive days. Both portions of the (α,p) distributions were measured in one continuous run. The greater difficulty experienced in matching the energies of the scattering measurements reflects itself in the somewhat larger energy differences between the two parts of the runs. In particular, the large error quoted for the elastic-inelastic run at 20.16 MeV is the result of a particularly poor energy match. On several occasions an adequate monitor measurement was not obtained, and in this case the energies were based on the spectrometer curves measured at the beginning or end of the day. The magnitudes of the errors have been increased accordingly to account for this fact. However, in all cases, the spectrometer measurements indicated that the *mean* beam energy was constant to within ± 30 keV over the period of a day; the uncertainties in the quoted values of the mean energies are larger because other sources of uncertainty are included.

The energy dependence of the angular distributions for alpha-particle groups corresponding to elastic scattering and inelastic excitation to the 4.43-MeV level of C^{12} and for the proton group leading to the ground state of N^{15} are presented in Figs. 3–5, respectively. The average interaction energies, as given in Tables I and II, are labeled directly below the corresponding angular distributions. Except for the angular ranges noted in the figure captions, the relative and absolute errors in the differential cross sections have been estimated to be 12 and 20%, respectively. The mean scattering angle of the solid-state detector system was found to have relative and absolute errors of $\pm 0.3°$ and $\pm 0.8°$, respectively. The average angular resolution for the detector apertures normally used was 1.3°.

The elastic-scattering distributions show a pronounced diffraction structure which varies slowly with energy at the forward angles. However, rapid variations are observed at the back angles, the nature of which can

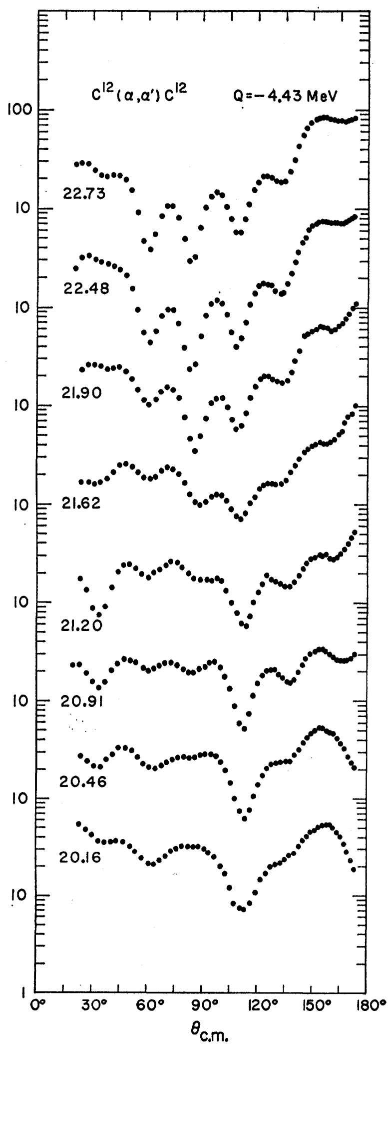

FIG. 4. Energy dependence of the $C^{12}(\alpha,\alpha')C_{4.43}^{12*}$ angular distribution. The ordinate is a logarithmic scale in mb/sr and the angular range is approximately 20° to 172° c.m. Statistical counting errors are less than 2% and the background subtraction errors are negligible.

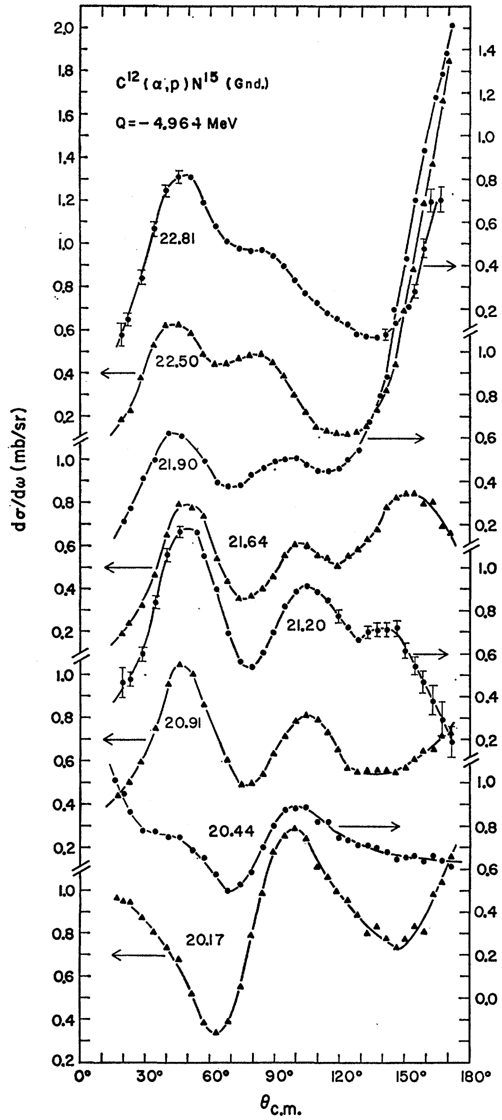

FIG. 5. Energy dependence of the $C^{12}(\alpha,p)N^{15}$(Gnd.) angular distribution. The ordinate is a linear scale in mb/sr and the angular range is approximately 20° to 172° c.m. Statistical counting errors are less than 3%. Typical error bars for the combined statistical and background subtraction errors are shown with the distributions at 22.81 and 21.20 MeV.

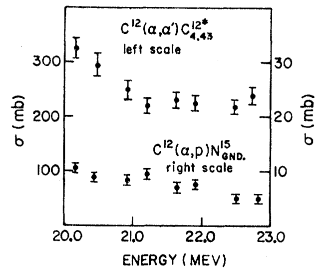

FIG. 6. Energy dependence of the integrated cross sections for the $C^{12}(\alpha,\alpha')C_{4.43}^{12*}$ and $C^{12}(\alpha,p)N^{15}$ (Gnd.) reactions. The integration ranges are from about 20° to 172° in both cases. The error bars represent relative errors of 16 and 13%, respectively, and include estimates of the error caused by neglecting the end portions of the distributions. The absolute errors in the integrated cross sections are approximately 30% in both cases.

best be seen by starting with the maximum centered over the 22.73-MeV energy label in Fig. 3. As the interaction energy is decreased, this peak has the appearance of splitting into two peaks, one of which moves out to larger angles and disappears while the remaining one appears to separate again at the lowest energies. Variations in the central angles can be seen by observing the deep minimum in the center of the top angular distribution and the peak just to the right of it. As the average interaction energy decreases, this minimum and peak merge together and become a shallow valley which deepens progressively with decreasing energy.

The inelastic scattering angular distributions are seen to change smoothly with energy. From an oscillatory pattern at the higher energies, the angular distribution degenerates into a somewhat irregular pattern with a broad valley around 110° at the lowest energy. Similar slow changes can be observed at the forward angles where a minimum appears and disappears, and at the backward angles where the angular distribution changes from a marked increase to a decrease. It is worth noting that the cross section measured at the extreme backward angles changes in magnitude by a factor of 10 within this energy range.

Strong backward peaking can be seen in the (α,p) distributions at the higher energies. This effect is particularly apparent in the distribution obtained at an energy of 21.90 MeV, where the backward peak exceeds the forward maximum by about a factor of 4. At 21.64 MeV, only 260 keV lower, this peak has disappeared. The angular distributions at the intermediate energies are characterized by an increase in the forward maximum while, at the lowest energies, the distributions show strong forward peaking and a large increase in the second maximum.

The integrated cross sections for inelastic scattering and the (α,p) reaction are shown in Fig. 6. Within the relative error bars, no appreciable structure exists in either case; the integrated cross sections tend to decrease with increasing energy.

IV. DISCUSSION

A comparison with the data obtained at other energies shows that the energy dependence of the three sets of angular distributions determined in this experiment is by no means unusual, but rather agrees with the general behavior observed at both higher and lower energies for the same scattering process. Likewise, throughout the energy region from 10 to 50 MeV, the distributions continue to exhibit direct-reaction features, but apparently cannot be explained by simple direct-reaction theories. A number of interpretations of the data have been suggested, but in general, they are only qualitative and sometimes obscure.

Studies of the elastic scattering show that the rapid variations in the angular distributions with energy, as seen here, persist to energies of 48 MeV and possibly higher. Mikumo[22] observes that the positions of the maxima and minima in the angular distributions do not shift systematically towards smaller angles with an increase in the energy as predicted by the strong absorption scattering model of Blair.[11] In the energy range from 10 to 19 MeV, studied by Carter,[17] major changes occur in the angular distributions within 500-keV energy intervals. Only qualitatively good fits could be attained with the optical and APB models in energy regions where the excitation functions are free of structure. By the addition of a resonance term to the APBM model, Carter was able to obtain reasonable fits for three of the 15 angular distributions using only one resonance term in the ℓth partial wave; however, for the remaining angular distributions, it was found that three or four resonance terms were required to fit the data at a given energy.

In the energy range from 27 to 48 MeV, the inelastic distributions show oscillations of about the same magnitude as the inelastic data presented in this paper, and similarly, the average magnitude of the differential cross section is about 10 mb/sr. In general, the inelastic distributions change with energy, but the fluctuations are usually smaller in magnitude than in the elastic scattering. The oscillations observed here in the angular distributions at 22.73 and 22.48 MeV are considerably more regular in spacing and amplitude than those observed at higher energies. In fact, the strongest oscillations and largest backward peaking are found to exist in the same angular distributions. This behavior is quite similar to that found by Corelli *et al.*[18] for elastic scattering at 18.0 MeV. Another feature of the data presented here is the agreement with the phase rule of Blair's inelastic diffraction model as was also noted by Mikumo.[22] Even when the inelastic oscillations become quite small, the phase rule appears to be obeyed very nicely for the first three oscillations in the distributions, and is approximately obeyed for the oscillations at the back angles. Inglis[45] has suggested that this phase relationship is simply a consequence of having strong

[45] D. R. Inglis, Nucl. Phys. 44, 460 (1963).

absorption and a short-range interaction. The inelastic scattering observed in the energy range from 10 to 19 MeV by Mitchell *et al.*[29] is similar to that observed here. The 4.43-MeV gamma-ray yield at 90°, as measured by the same group, is interesting in that above 11 MeV the existence of many overlapping levels is indicated.

The energy dependence of the (α,p) angular distributions shown in Fig. 5 is similar to, but less pronounced than, that observed by Priest *et al.*[32] in the energy range from 16 to 19 MeV. From 25 to 39 MeV, the distributions change gradually from backward to forward peaking with increasing energy.[34] Only partial success has been attained in applying direct-reaction theory using a knock-out process for the least bound proton for those distributions which are strongly peaked at the forward angles.[32,34]

A more detailed comparison with the data obtained independently at other laboratories within the energy range from 20 to 23 MeV verifies the results obtained here. In the elastic-scattering data of Jodogne *et al.*,[40] similar rapid variations are observed in the angular distributions, viz., the phenomena of peaks appearing to divide at the back angles and to disappear at the central angles for energy changes of approximately 400 keV. The qualitative behavior of the angular distributions is nearly identical. Although it is difficult to compare the back-angle cross sections because of the rapid angular variation of the distributions, both sets of data show a maximum in the back-angle peaking within the same energy range. It occurs at an energy of 21.7 MeV in the data of Jodogne *et al.*, and 22.0 MeV in the present work; the difference is amply covered by the energy errors of 300 and 120 keV, respectively. The magnitudes of the differential cross sections appear to agree within 10 to 20% over-all; the absolute errors in the cross sections are given there as 30% compared to 20% in the present work. A comparison was made with the (α,p) data of Yamazaki *et al.*[41] by plotting excitation functions at several center-of-mass angles from both sets of data. Within the fluctuations of the data, good agreement can be obtained by shifting the Japanese data 200 to 300 keV lower in energy and raising the magnitude of the cross section by 2 to 5%. The general behavior of the cross sections over the energy range common to both experiments is nearly identical. However, their integrated cross sections are 50% smaller than those obtained in the present work. The difference is only partially accounted for by their smaller range of integration (20° to 140°).

The data obtained for the (α,p) reaction in the present experiment show one previously unobserved feature that may be of some theoretical importance. From the lowest energy data of Nonaka *et al.*,[34] at 25.0 MeV and the highest energy data of Yamazaki *et al.*, at 22.0 MeV, it might be inferred that the strong back-angle peaking is maintained over the interval between these two energies. On the contrary, it can be seen from the (α,p) data in Fig. 5 that a decrease in the back-angle peaking

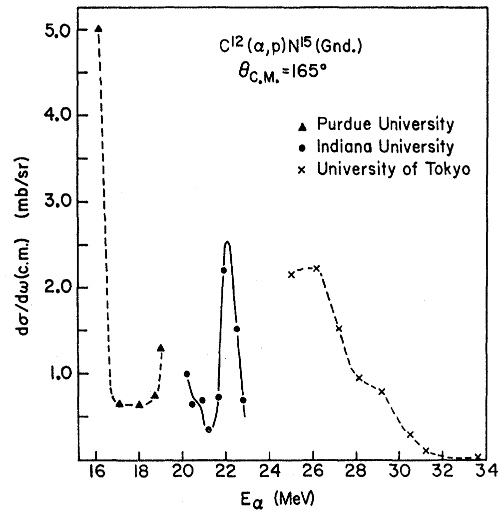

FIG. 7. The 165° c.m. excitation function for $C^{12}(\alpha,p)N^{15}$(Gnd.) reaction. A noticeable decrease appears in the back-angle peaking in the energy region slightly greater than 22 MeV. However, the peak width may not actually be as narrow as it appears. The peak is centered at an average laboratory interaction energy of 22.2 $\pm$0.1 MeV for the incident alpha particles, corresponding to an excitation energy of 23.6$\pm$0.1 MeV in the O^{16} compound system if it is formed.

occurs at energies of 22.50 and 22.81 MeV. This behavior is illustrated in Fig. 7, which shows the 165° excitation function for the (α,p) reaction. An extrapolation from the data of Priest *et al.*,[32] is represented by the triangles on the left and from the data of Nonaka *et al.*, by the crosses on the right. The solid dots represent the backward peaking in the (α,p) data of Fig. 5. The new data of Yamazaki *et al.* have not been plotted since they do not extend to 165° at all energies. The liberty has been taken of connecting the data points of the other laboratories with dashed curves and the data from Indiana University with a solid curve.

Several attempts have been made to fit the C^{12} $(\alpha,p)N^{15}$ back-angle data existing previous to the present experiment: Honda and Ui[46] invoked heavy-particle stripping, Teplov[47] considered the incoming particle to interact strongly with only a substructure of the nucleus, and Kromminga and McCarthy[48] interpreted the backward peaking in terms of interference between the normal stripping process and a term resulting from focusing of the incident waves by the optical potential. Added data from the present experiment presents a difficulty to the heavy-particle stripping since the observed energy variation is too rapid, and it does not appear that the use of reasonable values for the relevant parameters will enable other models to fit all the data now available.

Several suggestions have been put forth to explain the

[46] T. Honda and H. Ui, Nucl. Phys. **34**, 593 (1962).
[47] I. B. Teplov, Zh. Eksperim i Teor, Fiz. **42**, 211 (1962) [English transl.: Soviet Phys.—JETP **15**, 150 (1962)].
[48] A. J. Kromminga and I. E. McCarthy, Nucl. Phys. **24**, 36 (1961).

rapid energy dependence exemplified by the angular distributions presented in the present paper. One of the most common is that the data may be explained by a direct-reaction process interfering with compound-nucleus formation. The only quantitative application of this idea known to the authors is that due to Carter where a resonance term is combined with the APBM model. Unfortunately, in that approach, several resonances at a single energy are required to fit most of the low-energy data, thus allowing for the adjustment of eight to ten parameters. Since many of the features of a direct reaction are observed in the angular distribution, compound-direct interference with a dominant direct-reaction amplitude does represent a possible approach. It is interesting that much of the anomalous behavior is associated with quite small bumps in the total cross section.

Other suggestions rely solely on direct-reaction processes. One of the more promising direct-reaction theories from the standpoint of reproducing the observed energy dependence of the angular distributions is the extended optical model introduced by Buck.[16] Although this model was not successful in obtaining quantitative agreement with the low-energy data of Mitchell *et al.*,[29] it must be recalled that coupling with all excited states higher than the first was ignored, which is not likely to be a good approximation in this case. Recently Honda, Kudo, and Ui[49] have proposed that the back-angle peaking in the elastic scattering of alpha particles by C^{12} may be explained by heavy-particle stripping using a Be^8-α cluster representation for C^{12}. Although they successfully fit the data of Corelli *et al.*[18] at the back angles, the 180° differential cross section oscillates with a period of about 10 MeV, in contrast to the data shown in Fig. 3 where the period of oscillation appears to be on the order of 800 keV.

It is hopeful that more progress can be made from the experimental standpoint. Behavior similar to that observed for alpha-particle scattering by C^{12} has also been seen in the scattering of alpha particles by other light nuclei, e.g., N^{14} and O^{16}.[21,40] Rapid energy variations have also been observed by Mikumo[41] in the excitation functions for the $N^{15}(p,\alpha)C^{12}$ reaction leading to the ground state of C^{12}. In particular, a rather strong resonance occurs in the 150° excitation function at an energy corresponding to excitation of O^{16} to approximately 23.5 MeV. This resonance might be correlated with the resonance found in the present work in the 165° excitation function shown in Fig. 7. The excitation energy in O^{16} corresponding to this anomaly is found in the present investigation to be approximately 23.6 MeV, and the magnitude of the width is approximately the same as that observed by Mikumo for the inverse reaction. Another approach to the reaction mechanism operative in the scattering of alpha particles by light nuclei can be made through particle-gamma angular correlation measurements. The inelastic alpha-gamma angular correlation measurements of Eidson *et al.*[50] at 22 MeV, and McDaniels *et al.*[51] at 40 MeV, seem to indicate a predominantly direct-reaction process. Systematic studies over wide energy ranges for many light nuclei should establish more details and correlations in the anomalous scattering of alpha particles.

In conclusion, it is felt that systematic studies of the type presented here should be valuable in determining possible reaction mechanisms and testing various alpha-particle scattering theories. The nearly identical experimental conditions under which the data were obtained here introduces additional constraints. The interaction of alpha particles with light nuclei is not understood in detail, especially the rapid energy dependence as noted in the present paper. Studies of the angular distributions of scattered particles and various reaction products taken over a wide energy range under conditions of good resolution may show systematics which will aid in remedying this situation. It appears to be especially important that the angular distributions for elastic scattering be observed at large angles since the more interesting features occur at the largest angles where the nuclear penetration is the deepest, as was observed in the present experiment.

ACKNOWLEDGMENTS

The authors would like to express their appreciation to E. J. Ludwig and D. E. Blatchely for aid in taking the data. Dr. J. W. Mayer is to be thanked for providing the lithium-drifted detector. Communications with Dr. J. W. Mayer, Dr. H. M. Mann, and Dr. C. Inskeep concerning the lithium-drifted detector, and the aid of Dr. C. Inskeep in its rehabilitation, are especially appreciated. Helpful discussions of the experimental results with Dr. W. W. Eidson, Dr. J. G. Cramer, Dr. C. R. Gruhn, and Dr. N. S. Wall are gratefully acknowledged.

[49] T. Honda, Y. Kudo, and H. Ui, Nucl. Phys. 44, 472 (1963).

[50] W. W. Eidson, J. G. Cramer, D. E. Blatchley, and R. D. Bent, Bull. Am. Phys. Soc. 8, 11 (1963).

[51] D. K. McDaniels, D. L. Hendrie, R. H. Bassel, and G. R. Satchler, Phys. Letters 1, 295 (1962).