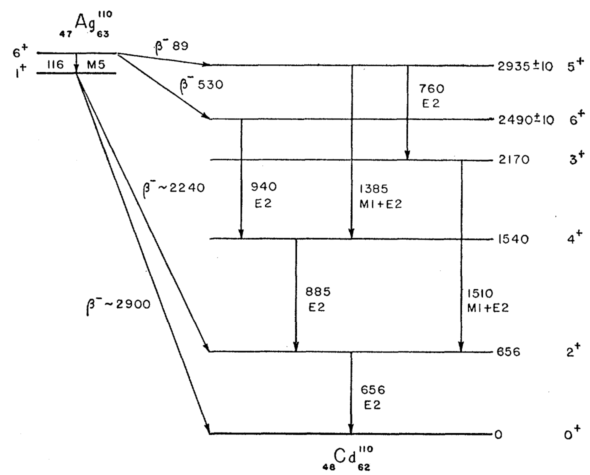

FIG. 6. Simplified decay scheme for Ag^{110m} showing those gamma-ray cascades which were used in the directional correlation studies. All energies are in kev.

in reference 6. Spins and parities consistent with the directional correlation measurements are indicated. Two well-established levels are not shown: a 2^+ level at 1480 kev and a level at 2220 kev of unknown spin. The 1385–885 kev cascade has the spin assignment $5^+(M1+E2)4^+(E2)2^+$, the 760–1510 kev cascade $5^+(E2)3^+(M1+E2)2^+$, and the 940–885 kev cascade $6^+(E2)4^+(E2)2^+$. The spin of the first excited state and the multipolarity of the 656-kev gamma ray have been determined from Coulomb excitation experiments with Cd^{110}.[28]

ACKNOWLEDGMENTS

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[28] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **98**, 1308 (1955).

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Light-Particle Spectra from the Nitrogen Bombardment of Oxygen

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Energy spectra and angular distributions were measured for protons and α particles resulting from the nitrogen bombardment of oxygen. It was found that the angular distributions of protons are reasonably isotropic whereas α particles are peaked in the forward direction. The energy distributions at various angles were compared with the predictions of a simple level density formula $w=C\exp[2(aE^*)^{\frac{1}{2}}]$. The constant a was found to be $a=2.5\pm0.2$ from proton spectra, $a=1.3\pm0.2$ from α-particle spectra at all angles measured. The energy spectrum of deuterons was measured at 15 deg and a value of $a=1.8\pm0.3$ was found. Unexplained structure was observed in the spectrum of α particles emitted at zero degrees. After correction for the phase space available and the barrier penetration, it was found that α particles are emitted on the order of ten times more copiously than protons, while deuterons are about half as abundant as protons.

INTRODUCTION

HEAVY-ION-INDUCED nuclear reactions at the energies available at this Laboratory are generally characterized by slow-moving incident particles, high energies of excitation due largely to the mass defects of the nuclei involved, and a variety of emitted particles. We concern ourselves here with protons, deuterons, and α particles which are produced from the nitrogen-oxygen reaction. The energy spectra of these particles, as well as their angular distribution in the forward hemisphere are reported here. The results are compared with predictions of a statistical evaporation process from a compound nucleus.

Previous work at this Laboratory has been concerned with energy spectra of light particles from lithium,[1] beryllium,[2] carbon,[3] nitrogen,[3] oxygen,[3] and aluminum[4] targets. In the last case, angular distributions of the emitted particles were also investigated. The present work is an extension of the last-cited reference, and is similar to it except that oxygen was used as a target instead of aluminum.

EXPERIMENTAL METHOD

Thin oxygen targets were prepared by heating clean copper foil, approximately 5 mg/cm² thick, in a furnace

* Operated for the U.S.A.E.C. by Union Carbide Corporation.

[1] C. D. Goodman, Bull. Am. Phys. Soc. Ser. II, **2**, 52 (1957).
[2] C. D. Goodman and J. L. Need, Phys. Rev. **110**, 676 (1958).
[3] C. D. Goodman, *Proceedings of the Conference on Reactions between Complex Nuclei*, Gatlinburg, Tennessee, Oak Ridge National Laboratory Report ORNL-2606, 1958 (unpublished).
[4] A. Zucker, Nuclear Phys. **6**, 420 (1958).

at 270°C for about half an hour. In this way oxide coatings containing approximately 0.1 mg/cm^2 oxygen were obtained. The amount of oxygen in the oxide layer was determined by weighing the foils before and after the heat treatment. Oxide layers were thus produced on both surfaces of the copper foil, but the nitrogen energy was sufficiently degraded after passing through the foil so that reactions with the oxygen on the back of the foil were rendered practically impossible by the Coulomb barrier. Reactions with the copper are similarly impossible because the beam energy is well below the Coulomb barrier of copper.

The targets were mounted on a rotatable holder in-

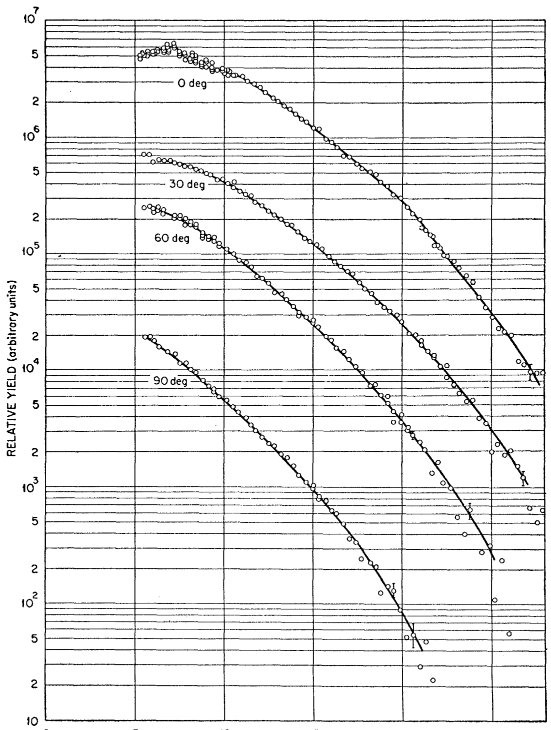

FIG. 1. Energy spectra of protons from the nitrogen bombardment of oxygen. The spectra at various angles are displaced from one another to avoid overlapping. Typical errors are shown.

side a small cylindrical reaction chamber 2.5 in. in diameter. The beam direction was perpendicular to the axis of the cylinder, with the axis of rotation coinciding with the axis of the cylinder. A peripheral slit $\frac{1}{2}$ in. wide and extending over an angular range of about 120 deg was covered with 0.5-mil Mylar foil through which reaction products could leave the chamber. After passing through the target, the beam was stopped by a 5.5-mg/cm^2 Ni foil. Light reaction products after leaving the chamber traversed a 4-cm air path and entered a proportional counter-scintillation counter telescope. The angular acceptance of this telescope, defined by a circular aperture, was ± 3 deg. The purpose of the telescope was to identify the particles and record their

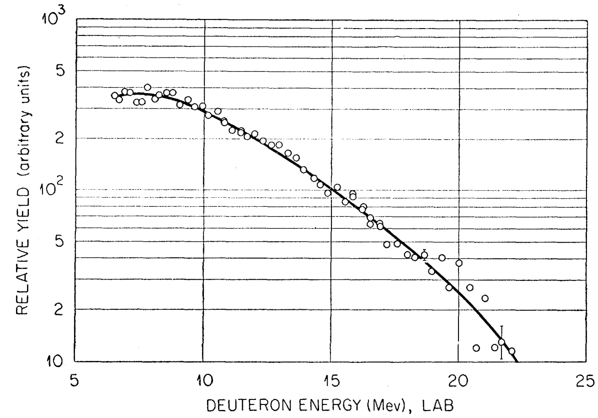

FIG. 2. Energy spectrum of deuterons at 15 deg from the nitrogen bombardment of oxygen. Typical statistical errors are shown.

energy at the same time by measurement of dE/dx and E. The operation of the counter system and its calibration were described previously.[2,4] The resolution of the NaI(Tl) scintillation counter was about 2.2% for 20-Mev protons. The proportional counter resolution varied somewhat from one run to the next, depending on the cleanness of the counter and on the gas pressure used. At 1.1 atmos a typical resolution was 12% when used for proton detection. For α particles, a pressure of $\frac{1}{3}$ atmos was usually used to minimize the energy loss in the counter.

The gain of the E channel, including photomultiplier tube, preamplifier, and amplifier, was calibrated at one- or two-hour intervals during all runs by means of the Zn^{65} γ ray. The complete energy distribution for the light particles of one type at a given angle was measured in two or three sections by repeated overlapping runs with a 20-channel pulse height analyzer.

The triply-charged N^{14} cyclotron beam was collimated to a $\frac{3}{16}$-in. diam circle, and typical beam currents were 0.05 to 0.1 μa. Larger currents deteriorated the target oxide layer. The incident beam energy was 27.6 Mev.

Energy spectra for α particles were taken every 15 deg from 0 to 90 deg in the laboratory system. For protons, energy spectra were determined at four angles in the same interval. Because of the low yield of deuterons, their spectrum was measured at 15 deg only. For angles smaller than 60 deg, the target was positioned so that the observed particles emerged normal to the foil. For larger angles the target was at 45 deg to the incident beam. The effective target thickness was included in the calculation of the mean beam energy in the target and the differential cross section. A vibrating-reed electrometer was used to monitor and integrate the beam.

RESULTS

The spectra of protons, deuterons, and α particles given in Figs. 1, 2, and 3 are plotted as a function of

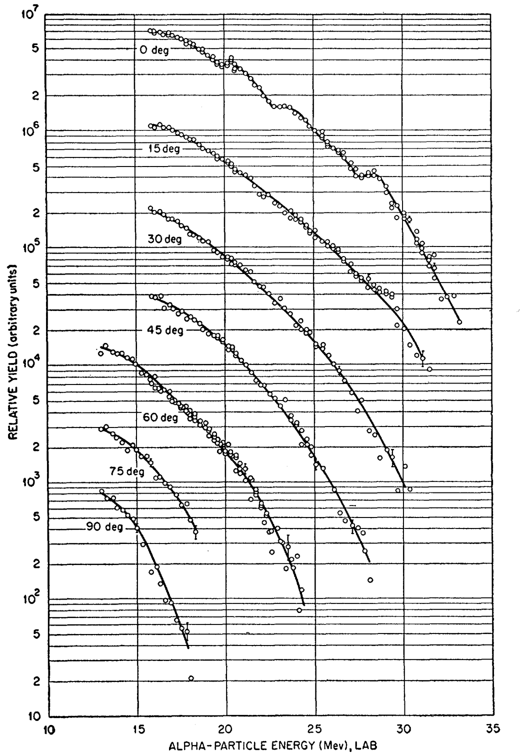

FIG. 3. Energy spectra of α particles from the nitrogen bombardment of oxygen. The spectra at various angles are displaced from one another to avoid overlapping. Typical statistical errors are shown.

the laboratory energy E. The number of counts per channel was corrected to number of counts per unit laboratory energy interval, using the energy *vs* pulse height calibration curves obtained by Goodman and Need.[2] The abscissa has been corrected for energy lost by the particles before entering the scintillator. The errors

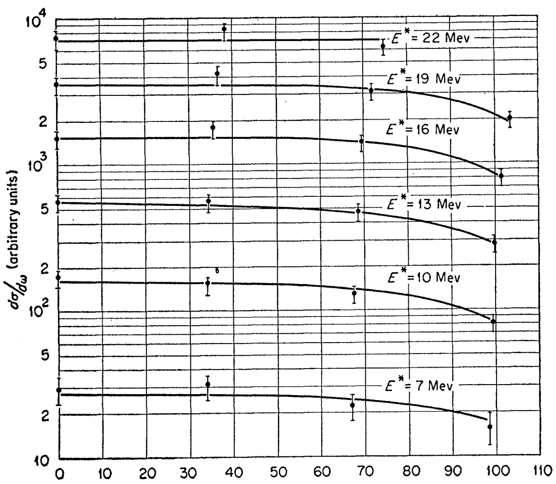

FIG. 4. Angular distribution of protons from the nitrogen bombardment of oxygen. The relative cross sections at various excitation energies are correctly represented by the ordinate.

shown are statistical errors only and do not include systematic errors, such as short-time drifts of the pulse height analyzing system. The fact that the data were readily reproducible leads us to believe that such systematic errors were not important.

The angular distributions of protons and α particles are shown in Figs. 4 and 5; the number of counts is given per unit excitation energy E^* in the residual nucleus. The center-of-mass angle, E^*, and the solid angle corrections are calculated on the assumptions that the target is O^{16} and that the particle observed is the first one emitted. The data were corrected for the nonlinearity of E^* as a function of E. Since runs were made on different targets whose thicknesses were not known precisely, the angular distributions were not calculated from the number of counts and the integrated beam intensity. Instead, every run at each angle was preceded and followed by a 0-deg run, and

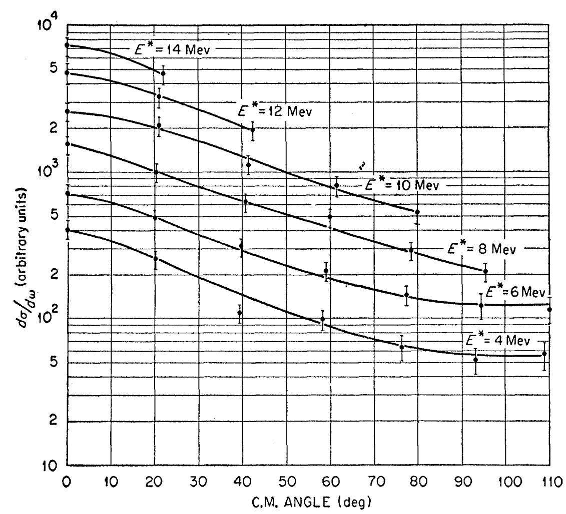

FIG. 5. Angular distribution of α particles from the nitrogen bombardment of oxygen. The relative cross sections at various excitation energies are correctly represented by the ordinate.

all counting rates were normalized to a 0-deg run. The errors shown on the angular distributions include statistical errors, as well as the uncertainties introduced by the normalization procedure.

No attempt was made to correct any data for the finite angular aperture, which means that in each case E^* and all necessary correction factors were calculated for the central ray only.

DISCUSSION

Nuclear reactions with heavy ions are undoubtedly very complicated and their mechanisms cannot at this time be rigorously described. It seems probable from the shape of the α particle angular distribution that a reaction mechanism is involved here other than a statistical breakup of a compound state. However, it is possible to extract some useful information even in a complicated situation. It has been the practice to in-

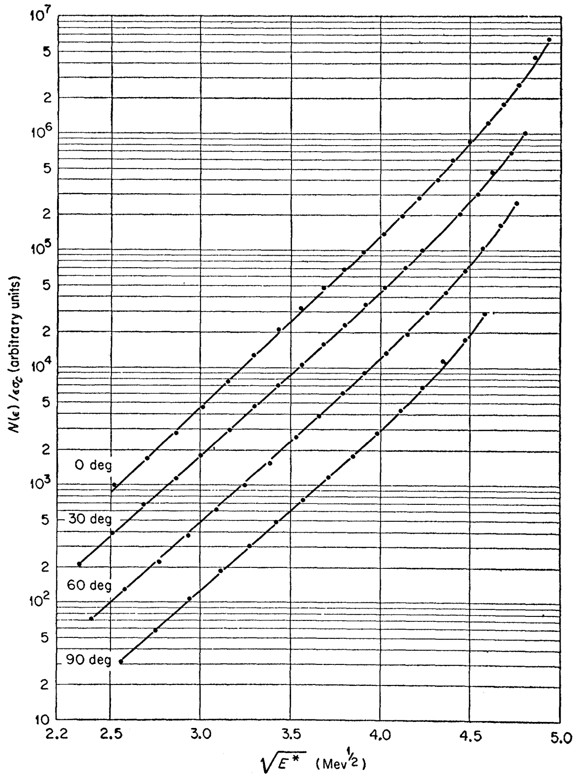

FIG. 6. Semilogarithmic plot of the normalized energy distribution of protons, as a function of the square root of the excitation energy of the residual nucleus. The curves at different angles are displaced arbitrarily to avoid overlapping.

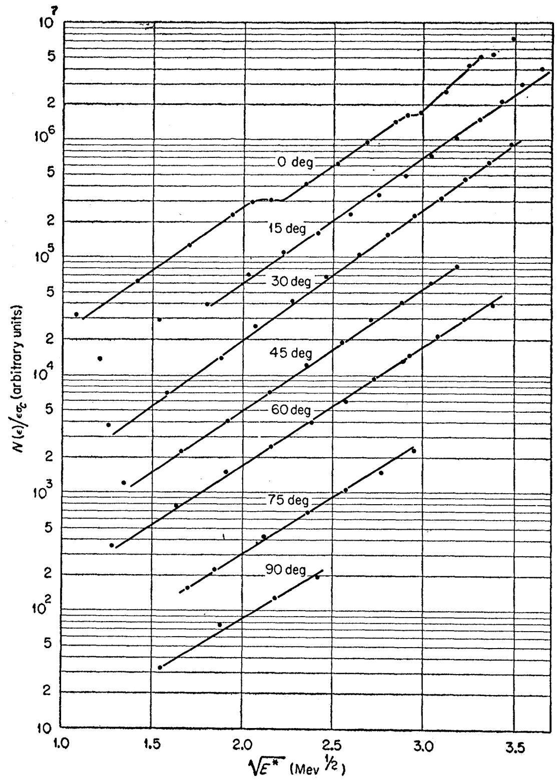

FIG. 7. Semilogarithmic plot of the normalized energy distribution of α particles, as a function of the square root of the excitation energy of the residual nucleus. The curves at different angles are displaced arbitrarily to avoid overlapping.

terpret data such as these in the light of a statistical evaporation from a compound nucleus. Even though such a mechanism may not be the only one occurring, this type of analysis provides a method for examining the data after removing barrier penetration, phase-space factors, and similar other effects extraneous to the reaction mechanism. Thus we will present values of a (defined below) mainly in order that they may be compared with those obtained elsewhere. The relative probability of emission of various particles will also be examined.

The energy spectra of light particles may be interpreted as a statistical evaporation from a compound nucleus. A simple treatment is outlined by Blatt and Weisskopf.[5] It predicts the probability for emission of a particle with channel energy between ϵ and $\epsilon+d\epsilon$ to be

$$N(\epsilon)d\epsilon = \text{const}\,\epsilon\sigma_c(\epsilon)w d\epsilon,$$

where σ_c is the capture cross section for the inverse process,[6] i.e., the capture of the particle in question by the residual nucleus, and w is the level density in the residual nucleus in the energy interval corresponding to $\epsilon+d\epsilon$. The value of ϵ is defined by $\epsilon = E_{\text{max}}^* - E^*$, where E^* is the excitation energy in the residual nucleus. The level density is approximately

$$w = C\exp[2(aE^*)^{\frac{1}{2}}].$$

Then $\ln[N(\epsilon)/\epsilon\sigma_c]$ plotted as a function of $\sqrt{E^*}$ is a straight line with slope $2\sqrt{a}$.

Such plots are shown in Figs. 6, 7, and 8 for protons, α-particles, and deuterons. It may be seen that the data treated in this way do indeed produce straight lines. The slope does not vary with angle. The values of a are as follows: $a = 2.5 \pm 0.2$ for Si^{29}, $a = 1.8 \pm 0.3$ for Si^{28}, and $a = 1.3 \pm 0.2$ for Al^{26}. The errors assigned to the a values were determined visually by fitting lines of various slopes to the calculated points.

The portion of the data at high excitation energy does not fit the straight lines. The deviation may be due to low-energy particles which have been emitted after the primary particle emission.

A peculiarity in the α-particle spectrum must be mentioned. As can be seen in Fig. 2, the 0-deg α spectrum exhibits structure. This structure was investigated in some detail in the course of the experiment. First, it was determined by placing absorbers in front of the counter telescope that the peaks are indeed due to alpha particles, i.e., the whole curve was shifted as would be expected for α particles, without a change in

[5] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), Chap. VIII.

[6] M. M. Shapiro, Phys. Rev. **90**, 171 (1953).

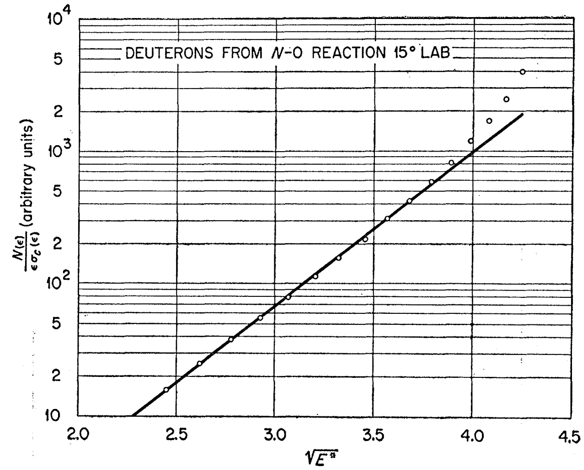

FIG. 8. Semilogarithmic plot of the normalized energy distribution of deuterons, as a function of the square root of the excitation energy of the residual nucleus.

the structure. Second, by replacing the target with a clean nickel foil of equivalent stopping power it was found that the peaks originate from the oxygen target, and that they are not due to some reaction products from the entrance collimator or to some unsuspected contamination in the beam. The question naturally arises why this structure appears only at zero degrees. It is possible that similar structure occurs at other angles, but shows up clearly only at 0 deg because the range of angles accepted by the counter system there is only half as large as it is at other angles, and the variation of laboratory energy with angle for any given excitation energy is at a minimum. In heavy-ion reactions structure of this sort has not been previously observed in any other α spectrum. It may conceivably be caused by an α particle structure of the target O^{16}. Further work is required to clear this up. The structure of the 0-deg spectrum is reflected also in the $\sqrt{E^*}$ plot in Fig. 7 where dips appear between portions of the curve which have approximately the same slope as that observed at other angles.

It is to be noted that the value of $a=1.3$ for α particles from oxygen is lower than one would expect from a relationship such as $a=A/f$, where f is of the order of ten.[7]

Another piece of information which may be gleaned from an experiment such as this is the relative number of protons, deuterons, and α particles emitted. In order to eliminate a number of factors unrelated to the reaction mechanism, a corrected probability of emission, P, is defined by

$$P=\frac{dN}{dI}\frac{1}{M\sigma_c\epsilon(2s+1)},$$

where dN/dI is the counting rate per unit incident beam, M the reduced mass of the emitted particle, ϵ its channel energy, s its spin, and σ_c the capture cross section obtained as before. Following these corrections, one may compare the value of P at any given excitation energy of the residual nucleus for various particles.

It is evident from the nature of the angular distributions of the α particles and the different values of a for protons, α particles, and deuterons that the ratios of the P values will vary widely both as a function of angle and as a function of energy. In Table I ratios of P for α particles and deuterons relative to protons are given at several angles and for typical values of E^* at which yields of different particles could be compared. At forward angles α particles are between one and two orders of magnitude more probable than protons. Also high-energy alphas (corresponding to low E^*) are more likely, relative to protons, than are low-energy alphas. It may be that in an oxygen target α particles are produced by a mechanism characterized by a forward peak and an excess of high-energy particles, compared to a more isotropic distribution and higher a which may be expected from a statistical evaporation process. However, even in the statistical evaporation from a compound nucleus α particles would be emitted more probably than protons because the residual nuclei are odd-odd and odd-A, respectively. Also, fewer deuterons than protons would be emitted since the residual nucleus for the former is even-even.

TABLE I. Reduced probability of emission of α-particles and deuterons relative to proton emission.

Particle	E^* (Mev)	θ_{lab} (deg)	P/P_{proton}
α	7	0	59
α	7	30	31
α	7	60	17
α	7	90	13
α	10	0	29
α	10	30	19
α	10	60	9.5
α	10	90	7.8
α	13	0	27
d	16.4	15	0.59

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[7] J. M. B. Lang and K. J. LeCouteur, Proc. Phys. Soc. (London) **A67**, 586 (1954).