Evaporation of Charged Particles from Highly Excited Compound Nuclei*

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Energy spectra and angular distributions of alpha particles and protons emitted in the bombardment of Ni targets with 160-Mev oxygen ions have been measured. The initial compound nucleus is characterized approximately by $Z=36$, $A=75$, total excitation energy $=125$ Mev, and rms angular momentum $=50\hbar$. The energy distributions have the shapes of evaporation spectra although they are displaced by several Mev toward lower energies compared to calculated evaporation spectra. The angular distributions are approximately symmetric about 90° and sharply peaked in the forward and backward directions. At all energies there is some excess of particles in the forward direction and at high energies the distributions are predominantly forward peaked. Most of the particles are believed to be evaporated from compound nuclei with angular distributions determined by the high angular momenta of the emitting systems. The angular distributions can be fitted by a theory with a single adjustable parameter which is related to the variation of level density with angular momentum and the incoming and outgoing angular momenta. The total cross section for alpha-particle production is 2.6 ± 0.6 barns and for protons 4.0 ± 1.0 barns. These cross sections are larger than the estimated cross section for compound nucleus formation, indicating that several charged particles are evaporated per interaction. About half the collision cross section is believed to result in compound nucleus formation.

INTRODUCTION

Most experiments in which compound nucleus formation is the predominant process involve bombardment with neutrons, protons, deuterons, or alpha particles with energies from a few Mev up to perhaps 40 Mev. A number of experiments have also been done with these particles at higher bombarding energies. The interpretation of a high-energy experiment, however, usually includes a "knock-out" process in which one or more nucleons are ejected directly from the target nucleus with high energy. This direct process produces compound nuclei with various excitation energies, and various values for Z and A, the distributions of which must be calculated. The compound nucleus then decays by the emission of light particles and eventually reaches a stable state.

The availability of beams of heavy ions at energies up to 10 Mev per nucleon makes it possible to extend the study of compound nucleus formation and decay to high excitation energies with less competition from direct interaction or knock-out processes. An oxygen ion with 160 Mev of kinetic energy is still a relatively slowly moving particle, comparable to a 10-Mev proton or a 40-Mev alpha particle. Thus a large amount of energy may be made available in a nuclear reaction with a heavy ion and the chance for immediate compound nucleus formation should be relatively high. The study of compound nucleus formation with heavy ions may give information on the Coulomb distortion of nuclei[1] because of the large Coulomb interaction energy of a heavy ion with a target nucleus. The study of the decay of the compound nucleus should give information related to level densities at high excitation energy and high angular momentum. Classically, large nuclear distortions may occur if compound nuclei are formed with high angular momenta.

It is usually stated that the decay of a compound nucleus is independent of the mode of its formation. The compound nucleus, of course, conserves the total energy and linear momentum with which it was formed. In addition, it has been pointed out explicitly that the total angular momentum of the system must be "remembered" in the decay of the compound nucleus. This has an effect on the angular distribution of particles emitted from the system.[2] A highly excited compound nucleus is expected to emit particles isotropically providing it is formed with an energy such that the level spacing is small compared to the level width, and the phases of the excited levels are random, and the variation of level density with angular momentum is proportional to $2J+1$. However, if the level density dependence on angular momentum differs from $2J+1$, there will be an angular correlation between the orbital angular momentum of an emitted particle and the angular momentum of the emitting system. The angular distribution of particles then is no longer isotropic but is still symmetric about 90° with respect to the beam direction, and approaches $1/\sin\theta$ in the limit of very high angular momentum. The maximum angular momentum involved in the collision of a 160-Mev oxygen ion with a medium or heavy target nucleus is of the order of $50\hbar$ to $100\hbar$. Thus one expects to see effects due to high angular momentum in the study of heavy-ion reactions.

This paper describes the results of experiments in which Ni targets were bombarded with 160-Mev oxygen ions. Measurements were made of the distributions in energy and angle of protons and alpha particles emitted from the target under bombardment. Other isotopes of hydrogen and helium were not separated experimentally but are believed to be produced with low yield.

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[1] G. Breit, M. H. Hull, Jr., and R. L. Gluckstern, Phys. Rev. 87, 74 (1952).

[2] T. Ericson and V. Strutinski, Nuclear Phys. 8, 284 (1958).

Equipment

The fully accelerated oxygen-ion beam of the Yale University heavy-ion accelerator was used. The beam emerges from the accelerator at a nominal energy of 10 Mev per nucleon, passes through an analyzing and focussing system, and enters the reaction chamber. The reaction chamber, the detectors, and associated equipment for identification of particles and measurement of their energies are described in detail elsewhere.[3] The system is described briefly here.

The beam enters the reaction chamber through a series of circular collimators, passes through a target, and leaves the chamber into a Faraday cup. Three collimators are used, two of which define the beam diameter at the target and the third of which does not define the beam but prevents particles scattered from the second collimator from entering the detectors. Up to six different targets are mounted in the chamber on a wheel which may be rotated from the outside through a vacuum seal to bring a given target into position. The detectors are mounted in the chamber lid inclined at an angle of $8\frac{1}{2}°$ to the horizontal plane containing the beam axis. The detectors may be placed to view the target at any angle with respect to the beam direction from $8\frac{1}{2}°$ in the forward direction to $171\frac{1}{2}°$ in the backward direction by rotating the lid.

The detecting system consists of a proportional counter and a CsI scintillation spectrometer. Particles enter the proportional counter through a grid-supported Ni window about 500 μg/cm^2 thick. The angle subtended by the entrance aperture from the target is about 1°. The path length for a particle through the proportional counter gas is about $1\frac{1}{4}$ in. The back wall of the counter is formed by the polished face of the CsI crystal. No barrier or light reflector is used between the proportional counter and the crystal.

Commercial P-10 gas (90% argon and 10% methane) is flowed through the proportional counter continuously. The pressure is maintained at the desired value by a commercially available regulating device (Manostat). Pressures of 15 cm to 60 cm of Hg have been used in the detection of protons and alpha particles. Typical proportional counter voltages at these pressures are 1200 and 1800 volts, respectively. The wire diameter is 0.005 in. Gas gains of about 100 are obtained under these conditions.

Coincident pulses from the proportional counter and the photomultiplier represent the initial rate of energy loss, dE/dx, and energy, E, of a particle passing through the system. These pulses have been used in two ways to identify and record energy spectra of particles. In the first method both pulses are amplified and passed through single-channel analyzers. The amplified E pulse is fed separately to a 20-channel analyzer which is in turn gated by the coincident output of the single-channel analyzers. The single-channel analyzers are set to pass E pulses over a certain minimum value and dE/dx pulses within one of four different ranges. In the uppermost range of dE/dx most of the alpha particles are obtained; in the next highest range appear the highest energy alphas and the lowest energy protons (overlapping in dE/dx but not in E); in the third range most of the protons appear; and in the fourth range, that of the lowest dE/dx pulses, the highest energy protons may, if necessary, be separated from coincident noise pulses which appear at low E. The alpha spectra are thus obtained in one or two pieces and the proton spectra in one to three pieces which may then be combined.

The second detection method which has been used involves the display of the amplitudes of the dE/dx and E pulses on the x and y axes of an oscilloscope. Points on the scope face due to particles of a given type then lie on an hyperbola. The scope face is then suitably masked so that particles of one type only appear and is viewed by a photomultiplier the output of which is used to gate the twenty-channel analyzer. This method of operation has the advantage over the method previously described that the entire spectrum of one type of particle may be taken at one time.

The targets used ranged in thickness from 500 μg/cm^2 to 2 mg/cm^2. Beam currents were of the order of 10^{-8} to 10^{-9} ampere time average (of O^{+8} ions). The beam of the heavy-ion accelerator is actually pulsed at 10 pulses per second with an over-all duty cycle of about 2%. This means that instantaneous beam currents during a pulse were about 50 times greater than stated above. Counting rates were held to approximately one count per beam pulse. At much higher counting rates the dE/dx pulse heights began to decrease. This effect is not understood in detail although it is probably related to the total ionization and may be a space charge lowering of the gas multiplication of the proportional counter.

The beam after passing through the target was collected in a Faraday cup. The cup was $1\frac{1}{2}$ in. in diameter and 6 in. deep and was used with no magnetic guard field or bias voltage. The integrated beam current for each run was measured with an electrometer. It was assumed in calculating the number of particles that the oxygen ions had a charge of +8 upon entering the cup.

Reduction of Data

The energy spectra of alpha particles and protons emitted at various laboratory angles from 17° to 171.5° have been recorded. At angles smaller than 17° elastically scattered particles interfered with the observation of alphas and protons. Preliminary results on the angular distribution of alpha particles emitted in this reaction have been reported previously.[4] A few alpha spectra from

[3] C. E. Anderson, A. R. Quinton, W. J. Knox, and R. Long, Nuclear Instr. and Methods **6**, 1 (1960).

[4] W. J. Knox, A. R. Quinton, and C. E. Anderson, Phys. Rev. Letters **2**, 402 (1959).

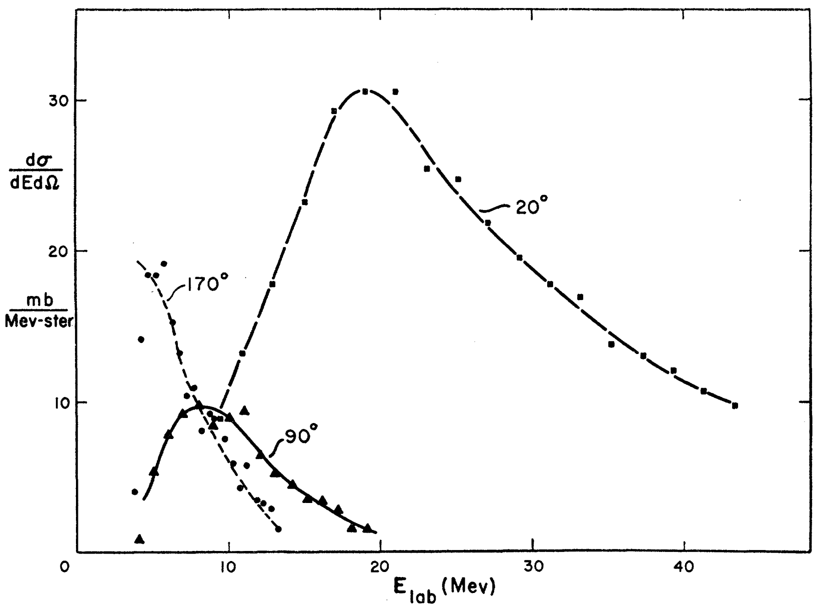

FIG. 1. Energy spectra of alpha particles emitted in the interaction of 160-Mev oxygen ions with Ni target nuclei. Spectra observed at three widely separated laboratory angles are shown. The shift in the energies of the particles with angle shows the large effect of the center-of-mass motion.

one set of results are shown in Fig. 1. The alpha data shown were taken by the method of gating the 20-channel analyzer with dE/dx pulses passing through a single-channel analyzer. The total number of counts in each spectrum ranges from about 1000 to 5000.

The apparatus was calibrated with alpha particles emitted by ThC (6.1 Mev) and ThC′ (8.8 Mev). The relative width (full width at half maximum) of the 8.8-Mev alpha line in the CsI crystal was at best about 7%. The relative width of the 8.8-Mev alpha line in the proportional counter at 60 cm Hg gas pressure and 1200 volts was about 10%. Calibrations were made before and during each run in order to determine the energy scale for alpha particles and protons and to check the apparatus for drift. The energy scale was determined usually by the position of the 8.8-Mev calibration peak.

The analysis of the data is described in more than the usual detail here because the center-of-mass transformation is such a large correction to data obtained in the study of a high-energy heavy-ion reaction. The raw data consist of numbers of counts in different channels of the multichannel analyzer. The channel number is proportional to the pulse height in CsI of particles which have left the target and passed through the detecting system. The particles are known to be protons or alphas by the methods of identification described above. The channel number scale was converted to an energy scale using the measured pulse-height response of CsI to protons or alphas.[5] The energy scale was corrected for energy losses of the particles in the target, counter window and proportional counter gas. Energy losses were computed using the data of Northcliffe[6] and Whaling[7] for alpha particles and of Bichsel[8] for protons. The number of counts in a channel was divided by the energy width of the channel in order to obtain a number proportional to the differential cross section per unit energy per unit solid angle in the laboratory frame of reference.

Each point in each spectrum has been transformed to the center-of-mass frame of reference. The average mass of nickel of natural isotopic abundance was used in computing the center-of-mass velocity. Because of the number of points to be transformed the transformations were made by an IBM 650 computer. The center-of-mass angle and energy were computed and the number of counts was then transformed to the center-of-mass system by the Jacobian relating the laboratory space in energy and angle to the corresponding center-of-mass space. The Jacobian turns out to be simply the ratio of the square roots of the center-of-mass and the laboratory energies.[9] It is considered desirable to use the two-dimensional Jacobian in the transformation (or some approximation of sufficient accuracy) since the correction is large and the spectra observed are continuous in energy rather than consisting of discrete groups as in much of low-energy nuclear spectroscopy.

Transformed data from different laboratory angles were used in order to reconstruct a center-of-mass energy spectrum at a given center-of-mass angle, or to construct the angular distribution for particles of a given energy in the center-of-mass system. Angular

[5] A. R. Quinton, C. E. Anderson, and W. J. Knox, Phys. Rev. **115**, 886 (1959).

[6] L. C. Northcliffe (private communication).

[7] W. Whaling, *Encyclopedia of Physics*, edited by S. Flügge (Springer-Verlag, Berlin, Germany, 1958), Vol. 34, p. 208.

[8] H. Bichsel, Phys. Rev. **112**, 1089 (1958).

[9] We are indebted to H. W. Broek for working out this particularly simple form of the transformation.

distributions for particles of various energies are shown in Figs. 2 and 3. Center-of-mass energy distributions are shown in Figs. 4 and 5.

Energy Spectra

The energy spectra in the center-of-mass system have been compared to spectra calculated by Dostrovsky, Friedlander, and Fraenkel for this reaction. The calculations consist of Monte Carlo determinations of the courses of evaporation cascades from highly excited compound nuclei.[10] The level density expression for a

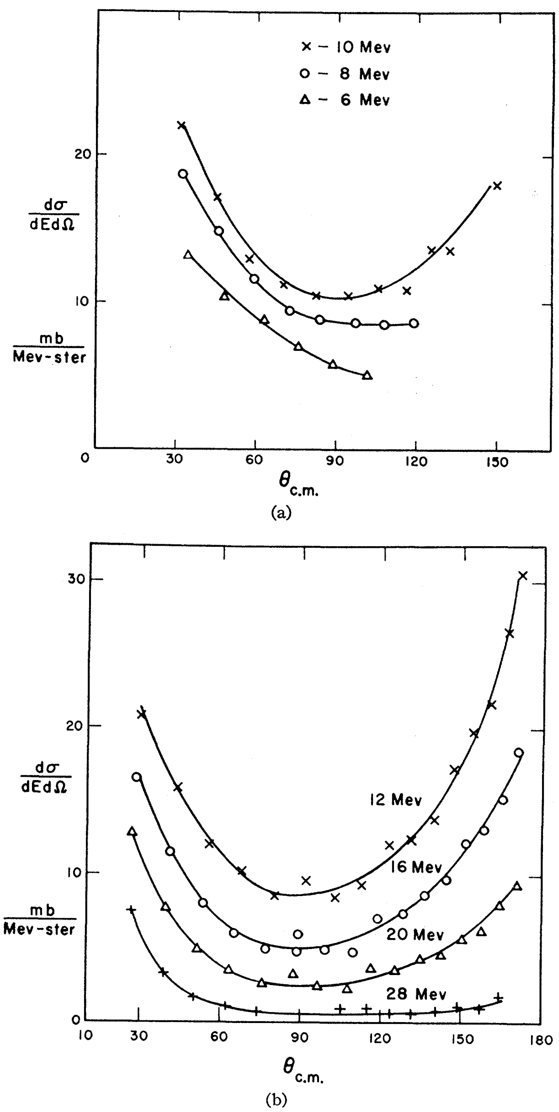

FIG. 2. Angular distributions of alpha particles in the center-of-mass system. The particle energy in the center-of-mass system is indicated for each curve.

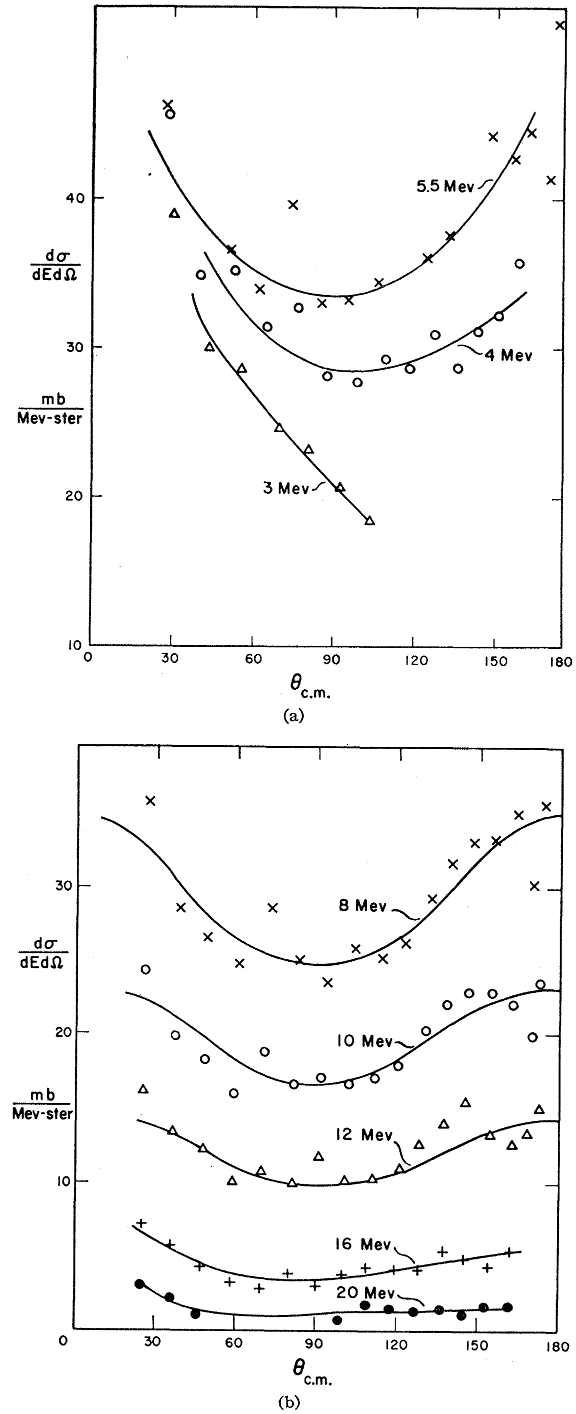

FIG. 3. Angular distributions of protons in the center-of-mass system. Center-of-mass energies are indicated for each curve.

degenerate Fermi gas;

$$\rho=\rho_0 \exp[2(aE)^{\frac{1}{2}}], \quad (1)$$

with a level density parameter $a=A/20$, and a radius parameter $r_0=1.5$ fermis, were used in the calculations.

[10] The program used in the calculations is described in detail by I. Dostrovsky *et al.*, Phys. Rev. **111**, 1659 (1958); **116**, 683 (1959).

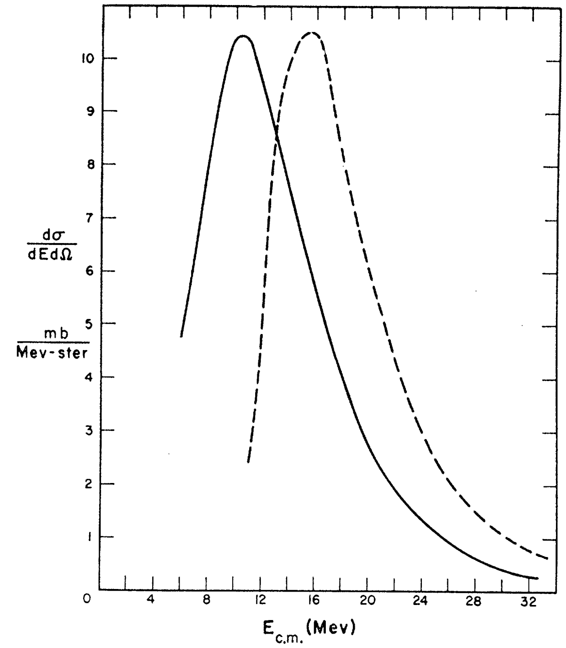

FIG. 4. Energy distribution of alpha particles at 90° in the center-of-mass system (solid curve). The dashed curve has been calculated for this reaction by Dostrovsky, Fraenkel, and Friedlander (see text). The calculated curve has been normalized to the same peak cross section as the experimental curve.

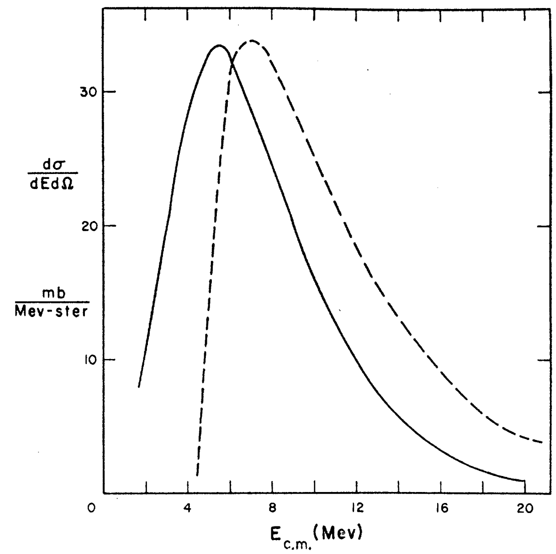

FIG. 5. Energy distribution of protons at 90° in the center-of-mass system (solid curve). The dashed curve has been calculated and normalized to the same peak cross section as the experimental curve.

Corrections were made in the level density expression for pairing, shell and symmetry effects. These calculations gave good fits to experimental excitation functions in the mass region $A=50$ to 75.[10] Figure 4 shows the alpha-particle spectrum from the O—Ni reaction compared to the calculated spectrum. The shapes are similar but there is about a 4-Mev displacement of the experimental spectrum toward lower energies. Figure 5 shows the experimental and calculated proton spectra. Again the shapes are similar but there is about a 2-Mev displacement of the experimental spectrum toward lower energies.

An explanation for the discrepancy is the possible lowering of the barrier for charged particle emission because of nuclear distortion due to the high angular momentum involved in the reaction. If a compound nucleus were formed in all collisions, the average initial angular momentum of the compound nucleus would be about 50 $\hbar$. The calculated minimum-energy liquid-drop spheroidal shape for such a system is a prolate spheroid rotating about a minor axis and with a major to minor axis ratio of about two. A rigid-body moment of inertia was assumed in calculating the distortion. Alpha particles and protons emitted through the points of this prolate spheroid would pass through a Coulomb barrier about 4 Mev and 2 Mev lower, respectively, than the barrier for a spherical nucleus. Unfortunately, however, similar discrepancies between calculated and measured emission spectra occur for reactions initiated by 200-Mev protons and 20-Mev protons in which the angular momentum of the compound system is not high.[11]

It has recently been shown by Fulmer and Goodman[12] that alpha-particle emission spectra in (p,α) reactions can be interpreted to indicate a lowering of the Coulomb barrier with increasing excitation energy. A correction of this type has been applied in the calculation of the energy spectra of charged particles evaporated in various reactions.[11] However, the barrier correction which gives reasonable agreement with evaporation spectra observed in reactions induced by 190-Mev protons,[13] predicts spectra for the O—Ni reaction which are lower than the observed spectra by several Mev.

A compensating effect which tends to raise the energies of evaporated particles in reactions involving high angular momentum has been pointed out by Nakasima and Kammuri.[14] They show that the same effect which gives rise to a strong angular correlation between the directions of emitted particles and the angular momentum of the emitting system, i.e., a level density which decreases strongly with increasing angular momentum, also increases the energies of emitted particles. It is possible that the lowering of the Coulomb barrier at high excitation energy and the angular momentum effect partially compensate in the explanation of the energy spectra of evaporated particles observed in heavy-ion reactions. No detailed

[11] Various experimental data have been examined and compared to calculations by I. Dostrovsky, Z. Fraenkel, and L. Winsberg, Phys. Rev. **118**, 781 (1960).

[12] C. B. Fulmer and C. D. Goodman, Phys. Rev. **117**, 1339 (1960).

[13] L. E. Bailey, University of California Radiation Laboratory Report UCRL—3334, 1956 (unpublished).

[14] R. Nakasima (private communication).

calculations including both of these effects have been made.

Angular Distributions

The angular distributions show minima at approximately 90° in the center-of-mass system and are strongly peaked in the forward and backward directions. For most of the particles the distributions are approximately symmetric about 90°. Qualitatively the energy spectra appear to be the same at all angles and of a shape which may be described approximately as a Maxwellian distribution cutoff on the low-energy side by a Coulomb carrier penetration factor. Thus the particles appear to be produced predominantly by evaporation from a compound nucleus. However, there is some excess of particles in the forward direction at all energies and the distributions are predominantly peaked in the forward direction for the relatively few particles with energies above 20 or 25 Mev. Direct interactions therefore compete with compound nucleus formation in the production of alphas and protons. The direct processes, however, have not yet been investigated in detail in the interaction of Ni with energetic oxygen nuclei.

The distributions of the lowest energy alpha particles and protons shown in Figs. 2 and 3 also appear to be peaked in the forward direction although there are not enough data at backward angles to know the shapes of the entire curves. As mentioned above, the center-of-mass correction for this reaction is very large and is the largest for the particles with the lowest velocities. Because of this, the low-energy data are the least reliable. Furthermore, particles with low center-of-mass energies emitted in the backward direction fell below the low-energy cutoff of the apparatus which was determined by the thicknesses of the target and proportional counter and by electronic noise. We do not know whether the apparent forward peaking of these low-energy particles is a real effect or not.

The maximum values for the angular momentum involved in the collision of two nuclei may be calculated from the expression

$$J_m^2 = 2\mu R^2(E-B), \tag{2}$$

where μ is the reduced mass, R is the sum of the radii, E is the kinetic energy in the center of mass and $B=Z_1Z_2e^2/R$ is the classical barrier energy. This gives a value for J_m of about 70 in units of $\hbar$ for a collision between a 160-Mev oxygen nucleus and a Ni target nucleus. This value is obtained using r_0 (nuclear radius parameter) equal to 1.5 fermis. The energy available in the center of mass for this collision is approximately 125 Mev.

If the level density over the entire range of energies and angular momenta involved in this reaction were proportional to $2J+1$, then no correlation would be expected between the direction of emission of particles and the direction of the angular momentum of the emitting system, i.e., particles would be emitted isotropically. However, it has been pointed out that on energetic grounds there must be a cutoff in the level density with increasing angular momentum. Classically there must be rotational energy associated with the angular momentum. In the limiting case there can be no levels for which the rotational energy exceeds the total reaction energy available in the system. Considerations of this general nature[2] lead to a level density distribution of the form

$$\rho(J) = \rho_0(2J+1)e^{-\alpha J(J+1)}, \tag{3}$$

where α can be expressed as a function of the nuclear moment of inertia and the nuclear temperature:

$$\alpha = \hbar^2/2\mathcal{G}T. \tag{4}$$

In these expressions contributions from higher order terms in the ratio of the rotational energy to the total excitation energy have been neglected. A level density distribution of this type leads to a correlation in which particles are emitted preferentially with their orbital angular momenta in the same direction as the angular momentum of the emitting system. Classically this corresponds to centrifuging particles off at the equator of the rotating system. Considered from either point of view, the residual nucleus tends to have lower angular momentum than the original compound system.

The result of Ericson and Strutinski for the angular distribution of emitted particles has been expanded to the form:

$$W(\theta) = 1 + (1/3)\beta^2 P_2(\cos\theta) + (1/35)\beta^4 P_4(\cos\theta) + (5/4186)\beta^6 P_6(\cos\theta)\cdots, \tag{5}$$

where

$$\beta^2 = \alpha_f^2 \langle J^2\rangle_{\text{av}} \langle l^2\rangle_{\text{av}}, \tag{6}$$

α_f is the level density angular momentum cutoff parameter for the residual nucleus of expression (3), and $\langle J^2\rangle_{\text{av}}$ and $\langle l^2\rangle_{\text{av}}$ are the mean square values of the angular momentum of the emitting system and the angular momentum carried away by the emitted particle, respectively. Average values of these quantities over an evaporation cascade must be estimated in order to compare calculated with experimentally observed angular distributions.

Figure 6 shows the angular distributions in the center-of-mass system of 12- and 16-Mev alpha particles emitted in the backward direction. The solid curve is expression (5) with β^2 adjusted to a value of 2.5 to fit the data. Figure 7 shows similar distributions for 6- and 10-Mev protons. The solid curve in this case is expression (5) with $\beta^2 = 0.68$.

The data chosen to be fitted have relatively good statistics and are relatively complete at backward angles compared to data at other energies. Relative errors from point to point in an angular distribution are believed to be primarily due to beam monitoring and are of the order of $\pm 10\%$. Errors due to counting

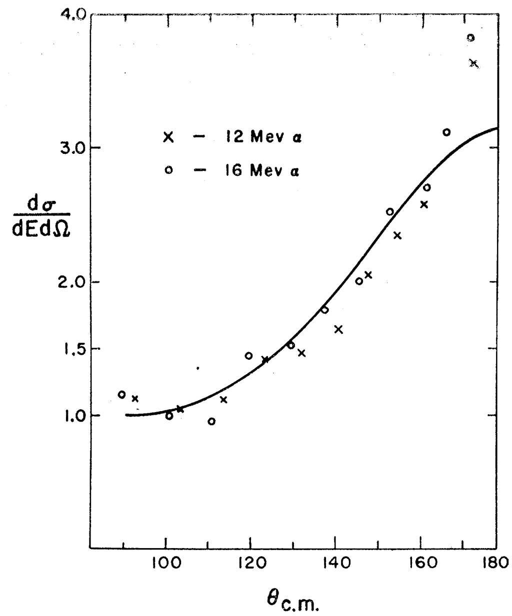

FIG. 6. The angular distributions of 12- and 16-Mev alpha particles emitted at backward angles in the center-of-mass system. The solid curve is expression (5) with β^2 adjusted to fit the data.

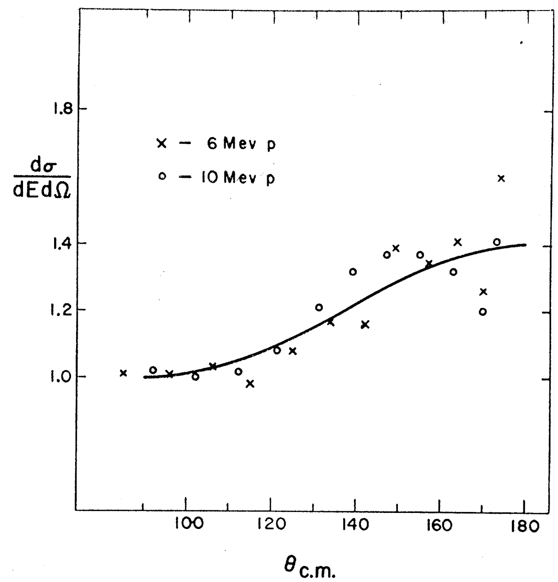

FIG. 7. The angular distributions of 6- and 10-Mev protons emitted at backward angles in the center-of-mass system. The solid curve is expression (5) with β^2 adjusted to fit the data.

statistics are somewhat smoothed in the reduction of the data. Data at backward angles only have been used in this comparison since the data as a whole suggest that direct interactions compete with compound nucleus processes at forward angles. Each set of data in Figs. 6 and 7 has been normalized to a value of 1.0 at 90°.

Using rigid-body moment of inertia, Fermi gas level density with $a=A/20$, $r_0=1.5$ fermis, and the initial values (before evaporation of any particles) for the angular momentum and nuclear temperature, one calculates the ratio of the experimental to the calculated values of β^2 to be 4.6 and 6.0 for alphas and protons, respectively. If values for J and T halfway down the cascade are used, these ratios are increased by a factor of 2.

The calculated value of β^2 may be increased by (1) increasing the angular momentum carried away by the evaporated particles, (2) decreasing the nuclear moment of inertia below the rigid-body value, or (3) demanding a steeper dependence of level density on excitation energy than given by Eq. (1) (equivalent to a lower nuclear temperature for a given excitation energy). It should be noted that neither nuclear distortion nor the level density dependence on angular momentum has been taken into account in estimating the angular momentum carried away by the outgoing particles. Either of these effects would increase the estimate of this angular momentum. Using the classical distortion effect alone and assuming perfect correlation of the angular momentum of the outgoing particle with that of the emitting system, a rough estimate is that the angular momentum carried away should be increased by a factor of 1.5.

If the nuclear moment of inertia is decreased substantially below the value for a rigid body, an excessive amount of rotational energy is required to accommodate the high angular momentum involved in this reaction. For example, the average angular momentum in the reaction under consideration is about 50 $\hbar$. If a spherical compound nucleus is formed with this angular momentum, and it is assumed to have rigid-body moment of inertia, the rotational energy is about 50 Mev. If the compound nucleus distorts to the liquid-drop, spheroidal, equilibrium shape, the rotational energy decreases to about 40 Mev.[15] This is about $\frac{1}{3}$ of the total excitation energy available in the collision. The moment of inertia cannot be decreased by more than a factor of 3 at this point without requiring that the rotational energy exceed the total excitation energy available in the reaction. In detail, of course, the equilibrium distortion would change if the moment of inertia were changed. The argument is merely meant to show that a large decrease in the moment of inertia is doubtful on energetic grounds in the case of a compound system of very high angular momentum.

Beard[16] has shown that the inclusion of the diffuseness of the nuclear boundary causes the level density to vary in such a manner that the nuclear temperature is appreciably lower at high excitation energies than predicted by the usual square-well Fermi-gas model. At the excitation energies under consideration the

[15] Example taken from calculations by E. R. Beringer and W. J. Knox.
[16] D. B. Beard, Phys. Rev. Letters 3, 432 (1959).

temperature in this model could be lowered by a factor of 1.5. Increasing the level density parameter from $A/20$ to $A/10$ also would lower the temperature by $\sqrt{2}$.

If the angular momentum carried away by evaporated particles were increased by 1.5 and the nuclear temperature were decreased by a factor of about 2 according to the above suggestions, the calculated values of β^2 would come into reasonable agreement with the observed values. We believe that this is the most reasonable way to obtain agreement although a nuclear moment of inertia less by a factor of about 2 than the rigid-body value cannot be excluded.

Cross Sections

Absolute cross sections were calculated using known target thickness, number of ions collected in the Faraday cup, and the computed solid angle subtended by the counter aperture from the target. Various measurements of the elastic scattering cross section for carbon and oxygen ions from gold and bismuth targets have shown that this system of monitoring and counting gives scattering cross sections which range from 80 to 100% of the calculated Rutherford cross section. The reason for the discrepancy is not known. Absolute cross sections calculated on the basis described above have been increased by a factor of 1.125 in the belief that this normalizes them on the average in a manner such that the equipment measures the theoretical value for the Rutherford scattering cross section. The absolute cross sections quoted are estimated to be accurate to about ±25% standard deviation. The ratio of the proton to alpha cross section is estimated to be correct to about ±15% standard deviation. The general reproducibility of the data, i.e., the measured number of counts under given experimental conditions at different times, was about ±10%.

The cross section obtained for the production of an alpha particle in the O−Ni reaction is 2.6 barns. The cross section for production of a proton is 4.0 barns. Other isotopes of hydrogen and helium have not been separated from protons and alpha particles in this experiment. The cross sections for their production are included in the above values. We estimate that they account for less than 10% of the observed particles.

Hubbard, Main, and Pyle[17] have measured total cross sections for production of neutrons in various heavy ion reactions. From their measurements we interpolate a cross section of 2.7 barns for the production of a neutron in the bombardment of Ni by 160 Mev oxygen ions.

Thomas[18] has calculated the cross sections for "compound nucleus formation," i.e., collision cross section, in heavy-ion induced reactions. From his calculations we interpolate a total cross section of 2.0 barns for the interaction of 160-Mev oxygen ions with Ni target nuclei.

[17] E. L. Hubbard, R. M. Main, and R. Pyle, Phys. Rev. **118**, 507 (1960).

[18] T. D. Thomas, Phys. Rev. **116**, 703 (1959).

TABLE I. Energy and angular momentum accounted for by evaporated particles in the O−Ni reaction.

Particle	Experimental production cross section (barns)	Number of particles per interaction[a]	Average energy carried away (Mev)	Average angular momentum carried away ($\hbar$)
α	2.6	1.3	16	5
p	4.0	2.0	32	4
n	2.7	1.4	18	3
Sum	···	4.7	66	12

[a] Assumes compound nucleus formation cross section to be equal to 2.0 barns, the calculated value for the total collision cross section (see text).

We may now discuss the energy and angular momentum balance in the O−Ni reaction from the compound nucleus point of view. The number of particles per interaction may be estimated by dividing the measured cross sections by the compound nucleus formation cross section. The energy carried away per particle has been estimated by taking an average over the measured spectrum and adding the binding energy (8 Mev for protons or neutrons, and zero for alpha particles). The angular momentum carried away by a particle has been estimated using the tabulated transmission coefficients for charged particles,[19] and using a classical approximation for neutrons, and has been averaged over the experimental energy spectrum. A spherical nucleus of radius-parameter $r_0=1.5$ f has been assumed. Table I shows the values thus calculated assuming that the compound nucleus formation cross section is equal to the entire calculated collision cross section (2.0 barns).

The total initial excitation energy in this reaction is about 125 Mev and the average angular momentum is about 50 $\hbar$. One sees from Table I that when estimated in this way, only about half of the excitation energy and about a quarter of the angular momentum is accounted for. We interpret this to indicate that only of the order of half the collision cross section results in compound nucleus formation. The angular momentum balance together with the angular distribution data may be taken to indicate that these particles carry away more angular momentum than estimated above. Neither nuclear distortion nor the variation of level density with angular momentum has been taken into account in estimating the angular momentum carried away. As mentioned previously a rough classical estimate on the basis of the nuclear distortion is that the angular momentum carried away should be increased by a factor of 1.5. If we now assume that half the collision cross section results in compound nucleus formation, and furthermore that the collisions of low

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

impact parameter are those resulting in compound nucleus formation, then the energy and angular momentum balance become reasonable. Under these assumptions the number of particles emitted per compound nucleus formed would be 2.6, 4.0 and 2.7 for α, p, and n, respectively. The $\bar{E}$ of Table I would be increased by a factor of 2, the $\bar{l}$ increased by a factor of 3, the excitation energy to be accounted for remains the same, and the average angular momentum to be accounted for would be reduced by a factor of $\sqrt{2}$.

The remainder of the collision cross section presumably gives rise to direct-interaction products. The cross section for direct interaction is known to be large in the O—Al[20] reaction. Our preliminary results indicate that fragments from Li to F are produced in the O—Ni reaction, that they are sharply peaked in the forward direction, and the cross section for these processes is substantial.

[20] C. E. Anderson, W. J. Knox, A. R. Quinton, and G. R. Bach, Phys. Rev. Letters 3, 557 (1959).

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Nuclear Resonance Fluorescence in Cu^{63}: Lifetimes of Excited States and the Slowing Down of Recoils (3–100 ev) in Condensed Media*

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Measurements of the lifetimes of the 669-kev and 963-kev states of Cu^{63} have been performed using the nuclear resonance fluorescence technique. Self-absorption experiments yield mean lives of $(2.94\pm0.24)\times10^{-13}$ sec for the spin $\frac{1}{2}$ 669-kev level and $(7.2\pm1.8)\times10^{-13}$ sec for the spin $\frac{5}{2}$ 963-kev level. The resonance yields from sources inside Cu metal and in water solution were measured. The reduction of the resonance yields due to slowing down of the recoils from the β^+ decay was calculated with the use of the model of Vineyard *et al.* for the solid and with an elastic collision model for the liquid environments. These calculations are in good agreement with the measured yields and result in a unique spin assignment to the 669-kev state. The effect of the scatterer temperature on the resonance yield was shown to be in agreement with the "effective temperature" predicted by the theory of Lamb.

I. INTRODUCTION

THE properties of the odd-mass Cu isotopes are particularly interesting since they are composed of a closed shell plus one odd proton in addition to the even number of neutrons. It might therefore be expected that a theoretical treatment of the properties of these nuclei would be relatively simple. Some theoretical investigations of these nuclei have been performed by Lawson and Uretsky.[1]

Extensive experimental investigations of the decay schemes,[2] magnetic moments, and quadrupole moments, have been performed. Coulomb excitation of the lower levels of these nuclei has been observed[3] and extensive inelastic particle scattering experiments have been carried out.

The success of any detailed theoretical study will depend upon the ability of the proposed model to predict the transition probabilities between the low-lying states. The partial lifetimes for the $E2$ part of the transition from the two lowest excited states in Cu^{63} and Cu^{65} are known from Coulomb excitation.[3] It might be expected that there would be substantial $M1$ contributions to these transitions. In 1954, Ilakovac[4] observed the nuclear resonance fluorescence of the 963-kev state in Cu^{63}. His results indicated that this transition is predominantly $M1$.

The improvements in the use of the resonance fluorescence technique suggested that further observations of the resonance in Cu^{63} would provide more accurate data on the lifetime and the yields from condensed sources. In addition to the detection of the 963-kev resonance, a surprisingly large fluorescence yield of the 669-kev first excited state of Cu^{63} was also observed.

Using the self-absorption method it was possible to obtain reliable values of the lifetimes of the 669- and 963-kev levels.[5] During the course of this investigation these resonances and their angular correlations were also observed by Rothem, Metzger, and Swann.[6] Observation of these resonances using a bremsstrahlung source has also been reported by Booth.[7]

Since the resonance yields in this case are large, and since very intense sources (~2 curies) of the parent

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[2] *Nuclear Data Sheets* (National Academy of Sciences, National Research Council, Washington, D. C.)
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[6] T. Rothem, E. R. Metzger, and C. P. Swann, Bull. Am. Phys. Soc. 5, 266 (1960).
[7] E. C. Booth, Bull. Am. Phys. Soc. 5, 239 (1960).