Alpha Particles and Protons Emitted in the Bombardment of Au^{197} and Bi^{209} by C^{12}, N^{14}, and O^{16} Projectiles*†

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(Received June 12, 1961)

Angular distributions, energy spectra, and absolute cross sections have been measured for alpha particles emitted in the bombardment of Au^{197} and Bi^{209} by C^{12}, N^{14}, and O^{16} projectiles at bombarding energies of 10.5 Mev/nucleon and for the C+Bi reaction at reduced energies of 8.7 and 7.1 Mev/nucleon. Angular distributions and absolute cross sections have also been measured for protons from the C+Bi and O+Bi reactions at bombarding energies of 10.5 Mev/nucleon. It was found that, from the angular distributions and energy spectra, it was possible to separate the contributions from direct and evaporation processes. The direct alpha particle results suggest that the principal direct process involved is the breakup of the incident projectile in an interaction with the surface of the target nucleus. At the 10.5 Mev/nucleon bombarding energies the cross sections for the emission of direct protons and direct alpha particles are found to be about 10% and 25–35%, respectively, of the calculated total reaction cross sections. The evaporation cross sections depend strongly on the excitation energy available in the compound system. The evaporation energy spectra can be fitted by an expression of the form $\exp(-E_\alpha/T)$ and the results yield an average level density parameter, $a=22\pm2$ Mev^{-1}, for these reactions.

INTRODUCTION

When heavy nuclei are bombarded by heavy ions, the nuclear reactions that are induced are of two general types. First, there are the compound-system processes which include fission and the evaporation of light particles. Competing with these compound-system processes are various direct processes. In these heavy-ion reactions, the major direct processes involve the breakup of the incident projectile and/or the transfer of one or more nucleons between the projectile and the target nucleus.

In previous papers[1,2] the results of an investigation of heavy-ion-induced fission reactions have been reported. Similar measurements have also been made by Gordon *et al.*[3] These results showed that for target nuclei in the region of gold the fission cross sections were significantly less than the estimated total reaction cross sections. At bombarding energies of 10.5 Mev/nucleon these results were consistent with the hypothesis that the cross section that is not taken up by fission went into direct projectile breakup type reactions. This was consistent with the large cross sections that have been obtained for the emission of heavy direct particles ($Z>2$) in the O+Al [4,5] and O+Au [6] reactions. Measurements on the evaporation of alpha particles in the O+Au reaction[7] have also indicated a large probability for the emission of direct alpha particles which presumably came from the breakup of the incident projectile.

Thus, by quantitatively investigating the characteristics of alpha-particle and proton emission in these heavy-ion-induced reactions, it should be possible to obtain information on both the direct and evaporation processes. Furthermore, by combining these results with the previous results on fission and the emission of direct heavy particles, information on the reaction mechanisms should become available.

In this experiment measurements have been made on the angular distributions, energy spectra, and absolute cross sections for the emission of alpha particles in the bombardment of gold and bismuth by carbon and oxygen projectiles at bombarding energies of 10.5 Mev/nucleon and for the C+Bi reaction at reduced energies of 8.7 and 7.1 Mev/nucleon. Measurements have also been made for the N+Au reaction at a bombarding energy of 10.5 Mev/nucleon. For protons, measurements have been made on the angular distributions and absolute cross sections for the C+Bi and O+Bi reactions at bombarding energies of 10.5 Mev/nucleon. These reactions and bombarding energies are the same as were used in the previous fission experiments.[1]

EXPERIMENTAL PROCEDURE

This experiment was performed with a detector consisting of a proportional counter backed by a CsI scintillation counter. The proportional counter measured the rate of energy loss (dE/dx) of any incoming particle while the scintillation counter measured its energy (E). This system and the scattering chamber which was used have been described in detail elsewhere.[8] Because of the gamma-ray background in the scintillation counter it was advantageous to use as small a

* This work was supported by the U. S. Atomic Energy Commission.
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1 H. C. Britt and A. R. Quinton, Phys. Rev. **120**, 1768 (1960).
2 A. R. Quinton, H. C. Britt, W. J. Knox, and C. E. Anderson, Nuclear Phys. **17**, 74 (1960).
3 G. E. Gordon, A. E. Larsh, T. Sikkeland, and G. T. Seaborg, Phys. Rev. **120**, 1341 (1960).
4 C. E. Anderson, W. J. Knox, A. R. Quinton, and G. R. Bach, Phys. Rev. Letters **3**, 557 (1959).
5 D. A. Bromley, M. Sachs, and C. E. Anderson, Bull. Am. Phys. Soc. **6**, 287 (1961).
6 W. J. Knox (private communication).
7 W. J. Knox, *Proceedings of the Second Conference on Reactions Between Complex Nuclei* (John Wiley & Sons, Inc., New York, 1960), p. 263.
8 C. E. Anderson, A. R. Quinton, W. J. Knox, and R. Long, Nuclear Instr. and Methods **7**, 1 (1960).

CsI crystal as possible. For this reason, most of the alpha-particle data were taken using a 1-mm thick CsI crystal. This was thick enough to stop the most energetic alpha particles but would not stop all of the protons. The data on the proton emission from the C+Bi and O+Bi reactions were taken using a $\frac{5}{16}$-in. CsI crystal.

Energy spectra for the alpha particles and protons were obtained by analyzing the E pulses from the scintillation counter. The particles were identified by gating the analyzers with appropriate portions of the dE/dx spectrum from the proportional counter. The dE/dx pulses were sorted in a four-channel analyzer and the outputs of the four channels were used to gate four 100-channel analyzers which simultaneously analyzed the pulses from the E counter. With appropriate settings for the channel widths for the four-channel dE/dx analyzer it was possible to obtain a good separation between protons, alpha particles, and any heavier mass particles. In a typical case the widths could be adjusted so that channel No. 1 contained high-energy protons separated from noise, channel No. 2 contained high-energy alpha particles separated from low-energy protons, channel No. 3 contained only alpha particles and channel No. 4 contained any heavier mass particles. Thus, the proton and alpha-particle pulse-height spectra could be obtained simultaneously, by reconstruction from the spectra from the four 100-channel analyzers.

For the alpha-particle experiments, an energy calibration was obtained using a He^4 beam and observing elastically scattered alpha particles. Several calibration points were obtained by reducing the He^4 beam energy. During a run the system was periodically checked for drifts by observing the elastically scattered heavy ions and by use of a ThC, ThC′ alpha-particle calibration source. For the proton experiments the system could be calibrated using recoil protons from a polyethylene target.

The beam was monitored by collecting it in a Faraday cup which was connected to a current integrator. Absolute cross sections were determined by normalizing to Rutherford scattering at small angles as has been described in the previous paper.[1] The absolute cross sections determined by this method are estimated to be accurate to about 10%.

The targets used were a 2.5-mg/cm² gold foil and a 5.8-mg/cm² bismuth foil. The bismuth foil was prepared using the method that has been previously described for the preparation of thin carbon films.[9]

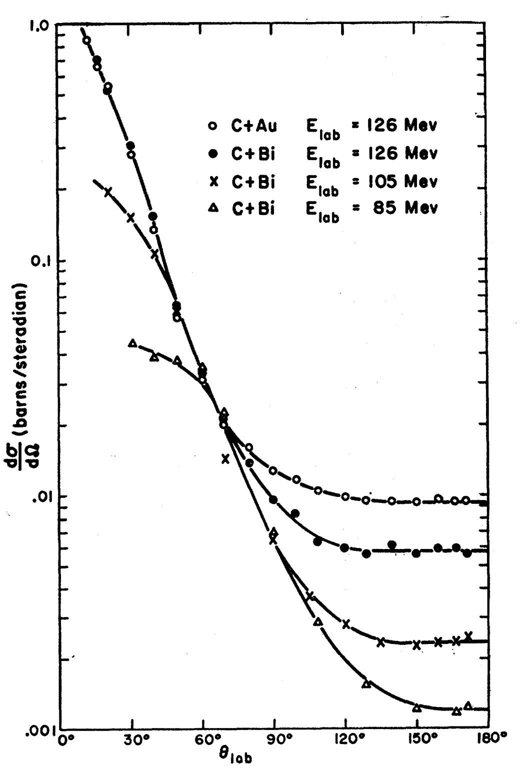

FIG. 1. The laboratory angular distributions for alpha particles emitted in the carbon induced reactions. Individual points are estimated to be accurate to about 10%.

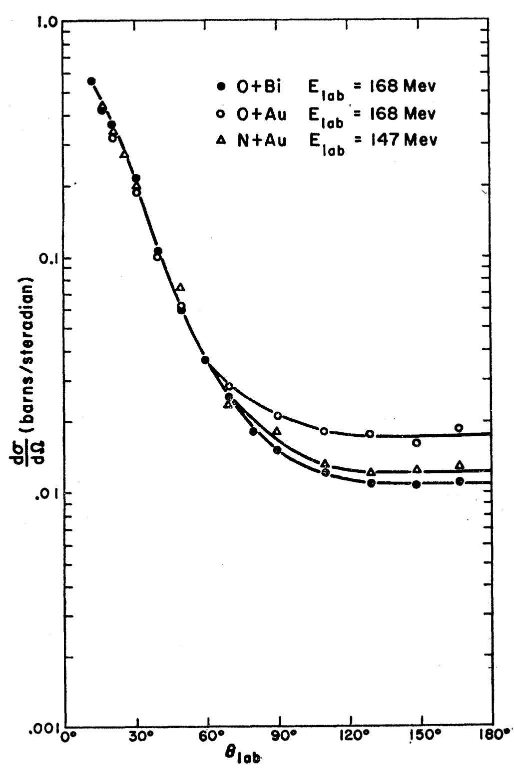

FIG. 2. The laboratory angular distributions for alpha particles emitted in the oxygen and nitrogen induced reactions. Individual points are estimated to be accurate to about 10%.

[9] G. Dearnaley, Rev. Sci. Instr. **31**, 197 (1960).

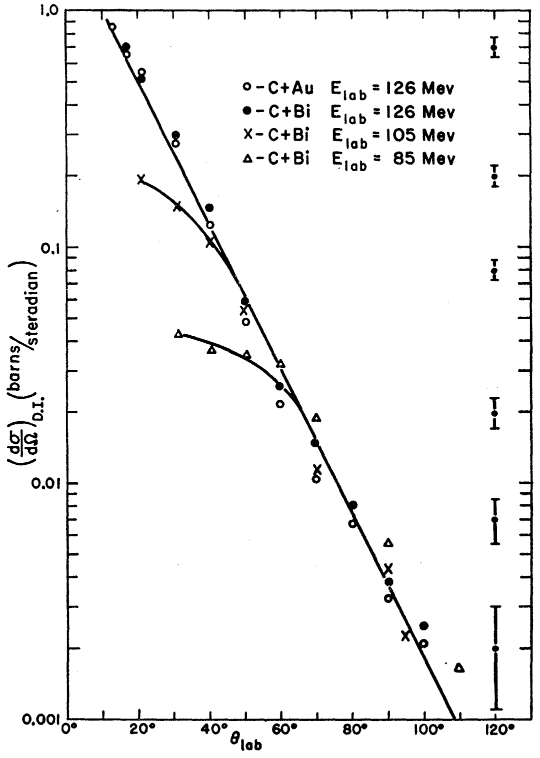

FIG. 3. The laboratory angular distributions for direct alpha particles emitted in the carbon induced reactions. Characteristic error bars are shown at the side.

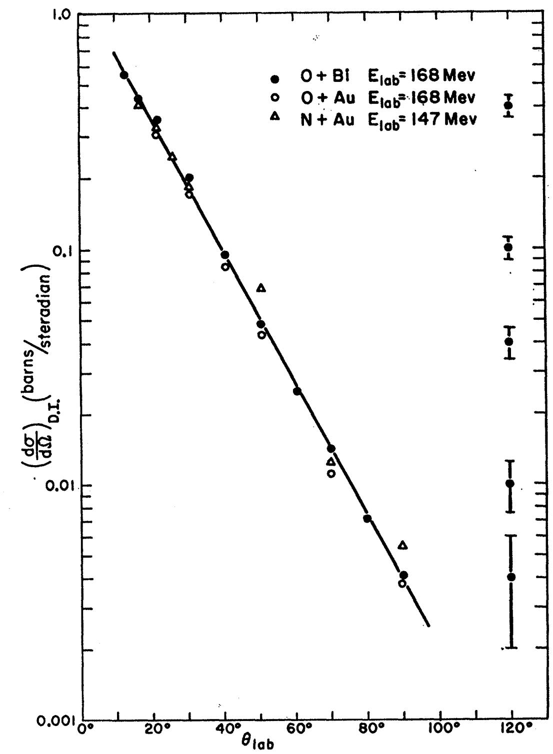

FIG. 4. The laboratory angular distributions for direct alpha particles emitted in the oxygen and nitrogen induced reactions. Characteristic error bars are shown at the side.

RESULTS

A. Angular Distributions

Figures 1 and 2 show the angular distributions for alpha particles emitted in the carbon-induced reactions and the oxygen- and nitrogen-induced reactions, respectively. These angular distributions show the characteristics of two different mechanisms which can lead to alpha-particle emission. At forward angles $d\sigma/d\Omega$ increases very rapidly with decreasing angle and is dependent only on the type and energy of the projectile, indicating the presence of some type of direct process. However, at far backward angles $d\sigma/d\Omega$ is relatively independent of angle, and the values of the cross section obtained from the various reactions are dependent on the excitation energy available in the compound system. In this case then, an evaporation-type process is the likely mechanism. This division is also suggested by the observed energy spectra. At far forward angles, the energy spectra are broad with the peaks at energies near the energy of an alpha particle moving with the velocity of the incident projectile. On the other hand, the spectra observed at the far backward angles peak near the classical Coulomb barrier for the compound system.

Because of the high excitation energies the angular distributions of evaporated alpha particles should be symmetric about 90° in the center-of-mass system if it is assumed that the phases of the levels are distributed randomly. Using this it is then possible to separate the contributions from these two processes. This was done by obtaining the angular distributions for the evaporation alpha particles from the data taken at far backward angles and then subtracting from the observed total angular distributions. The resulting angular distributions for direct alpha particles are shown in Figs. 3 and 4. For the 10.5-Mev/nucleon beams, the direct component, $(d\sigma/d\Omega)_{D.I.}$, is found to increase approximately exponentially with decreasing angle and to within the accuracies of the points the C+Bi and C+Au reactions yield the same results. Also the O+Bi, O+Au, and N+Au results are all the same to within the accuracies of the points, but it is interesting to note that the same exponential cannot be used to fit both the carbon results and the oxygen and nitrogen results. It is also interesting that the reduced-energy C+Bi results follow the same exponential at large angles but fall off at small angles; the angle at which they join the 10.5-Mev/nucleon curve increases with decreasing energy.

The laboratory angular distribution for protons emitted in the C+Bi and O+Bi reactions are shown in Fig. 5. These results show that the evaporation cross sections are greater for protons than for alpha particles but that for the direct particles, the reverse is true.

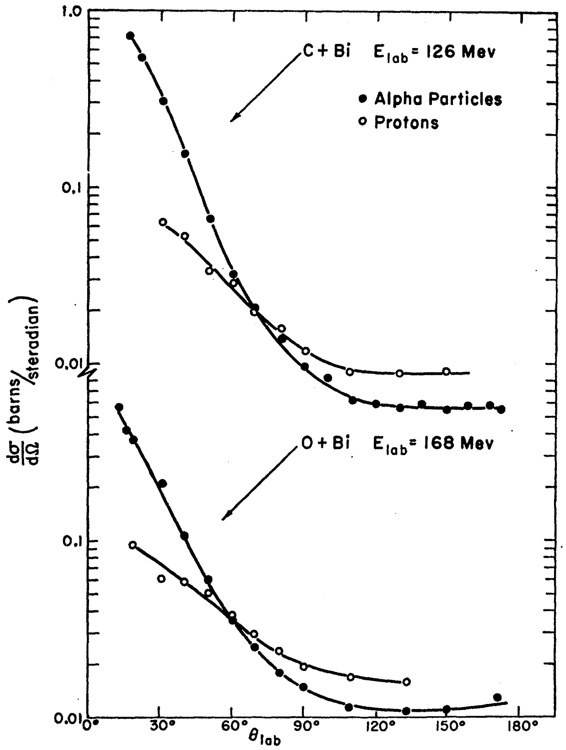

FIG. 5. The laboratory angular distributions for alpha particles and protons emitted in the C+Bi and O+Bi reactions at bombarding energies of 10.5 Mev/nucleon. Individual pionts are estimated to be accurate to about 10%.

The angular distribution for direct protons is shown in Fig. 6. In this case the results from the carbon and oxygen reactions can be fitted by the same curve and the angular distribution is less sharply peaked forward than for the direct alpha particles.

B. Cross Sections

From the angular distributions shown above, total cross sections were determined for the production of alpha particles and protons by the two processes. These results are given in Table I. The total evaporation cross sections are estimated to be accurate to about 10%. The total direct cross sections were determined by subtracting the estimated evaporation cross sections from the total cross sections for the production of alpha particles or protons. These cross sections were determined in each case from the experimentally observed laboratory angular distribution. A large part of the uncertainty in the total direct cross sections is due to the uncertainty in the extrapolation of the angular distribution to 0°. The uncertainties quoted are those of the absolute values of the cross sections and since the extrapolations of the angular distributions were all made in a similar way, the relative accuracies of the direct cross sections are probably somewhat better than these estimated uncertainties indicate.

ANALYSIS AND DISCUSSION

A. Evaporation Angular Distributions

The method described above for separating the angular distributions for the alpha particles from direct and evaporation processes yields the angular distribution of direct alpha particles quite satisfactorily. However, the angular distributions that are obtained for the evaporation alpha particles are not accurate enough to yield any additional information on the evaporation process. This is essentially because the anisotropies in the evaporation angular distributions are small because of the relatively small rotational energies involved in these reactions. For example, for the 10.5-Mev/nucleon C+Au reaction the observed anisotropy, $W(180°)/W(90°)$, in the center-of-mass angular distribution is 1.20 ± 0.20. From the evaporation theory as presented by Ericson[10] to first order in $\cos^2\theta$, the angular distribution should have the form

$$W(\theta)\simeq 1+(m_\alpha R^2/j)(E_{\text{rot}}/2T)\cos^2\theta,$$

where R, j, and T are the radius, moment of inertia, and temperature of the compound nucleus, respectvely, and E_{rot} is the rotational energy. Using a rigid-body moment of inertia this predicts an anisotropy of 1.09. Previous results on the evaporation of protons and alpha particles in the O+Ni reaction[11] and neutrons from various heavy-ion reactions[12] have yielded anisotropies

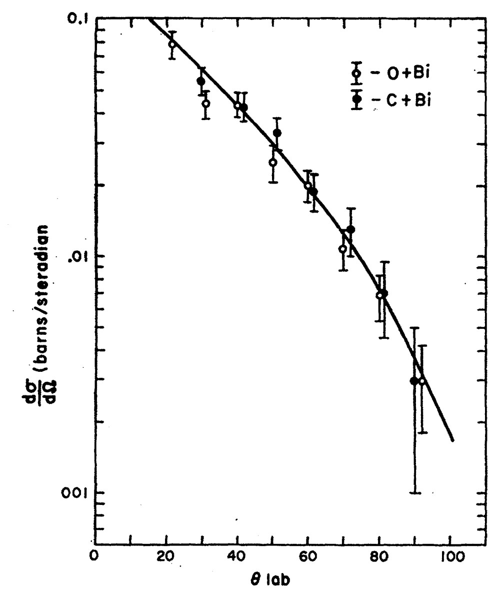

FIG. 6. The laboratory angular distribution for direct protons from the C+Bi and the O+Bi reactions at bombarding energies of 10.5 Mev/nucleon.

[10] T. Ericson, *Advances in Physics*, edited by N. F. Mott (Taylor and Francis, Ltd., London, 1960), Vol. 9, p. 425; see Secs. 3 and 4.
[11] W. J. Knox, A. R. Quinton, and C. E. Anderson, Phys. Rev. **120**, 2120 (1960).
[12] H. W. Broek, Phys. Rev. (to be published).

that were somewhat greater than those predicted using rigid-body moments of inertia. To be consistent with these previous results the anisotropy for the 10.5 Mev/nucleon C+Au reaction should be of the order of 1.3 to 1.4. Thus, because of the large uncertainty, the experimental anisotropy is consistent with either the previous results or the value predicted using a rigid-body moment of inertia. Similar results are obtained from all of the other angular distributions of evaporated alpha particles and protons.

B. Evaporation Cross Section

The cross sections for the evaporation of protons are found to be about 50% greater than for the evaporation of alpha particles. This is the same as the ratio of protons to alpha particles that was observed previously for the O+Ni reaction.[11] However, the actual cross sections are a factor of 20–40 less than those observed for the O+Ni reaction. This is to be expected because the larger barriers and lower temperatures, for these reactions with heavy targets, inhibit charged-particle evaporation.

For the reactions studied the ratio $\sigma_{\alpha,\mathrm{evap}}/\sigma_c$, which is the probability for evaporation alpha-particle emission, was found to vary smoothly with the initial excitation energy for the compound nucleus as is shown in Fig. 7. The abscissa E^* is the maximum energy available to an alpha particle evaporated from the full compound nucleus and was calculated from Cameron's mass tables.[13] These results show that the probability of alpha-particle emission is strongly dependent on the excitation energy available. This indicates that, in most cases the alpha particles are emitted early in the de-excitation cascade. The fact that the points from the carbon- and oxygen-induced reactions fall on the same curve gives some indication that the probability of alpha-particle emission is not strongly dependent on the angular momentum of the compound system. One effect that is expected, due to the large angular momenta, is the lowering of the level density because of the energy that must be tied up in collective rotation. For these heavy compound nuclei the moments of inertia are large, so that the energy tied up in rotation becomes relatively small. In the 10.5 Mev/nucleon C+Au and O+Au reactions the average rotational energies are 6.6 and 11.5 Mev, respectively, if rigid-body moments of inertia are used and the average angular momentum is taken from Thomas' calculations.[14] Actually, the average rotational energy may even be somewhat lower than this since the large probability of direct interactions should decrease the probability of forming compound nuclei in the grazing collisions which lead to the highest angular momentum states. This angular momentum effect which amounts to the lowering of the excitation energy by an amount equal to the average rotational energy would not be seen in the results presented in Fig. 7 because of the uncertainties in the evaporation cross sections. Another angular momentum effect that might be expected to show up in these results is an increase in the alpha-particle emission probability because of a lowering of the Coulomb barrier due to a distortion of the compound nucleus in the high angular momentum states. However, these results indicate that this effect must also be relatively small.

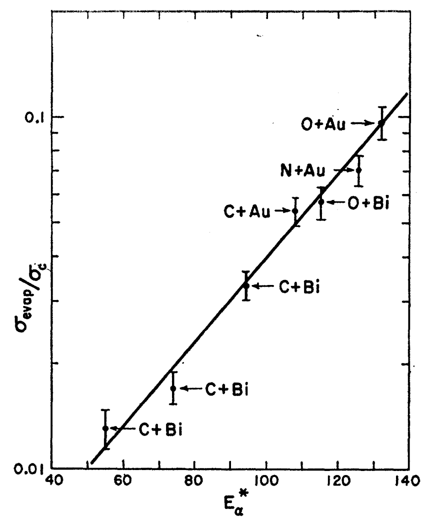

FIG. 7. The variation of the ratio of the total experimental evaporation alpha-particle cross sections to the estimated total reaction cross sections with the maximum energy available to an alpha particle evaporated from the initial full compound nucleus. The estimated total reaction cross sections are obtained from reference 14.

TABLE I. The total cross sections for the production of alpha particles and protons by direct and evaporation processes for the reactions studied.

Reaction	E_{lab} (Mev)	$\sigma_{\alpha,\mathrm{evap}}$ (b)	$\sigma_{\alpha,\mathrm{D.I.}}$ (b)	$\sigma_{p,\mathrm{evap}}$ (b)	$\sigma_{p,\mathrm{D.I.}}$ (b)
C+Bi	126	0.073	0.85±0.15	0.11	0.21±0.06
	105	0.030	0.41±0.10		
	85	0.015	0.18±0.05		
C+Au	126	0.12	0.83±0.15		
N+Au	147	0.16	0.56±0.10		
O+Au	168	0.22	0.54±0.10		
O+Bi	168	0.13	0.58±0.10	0.20	0.26±0.09

C. Evaporation Energy Spectra

Because of the large moments of inertia and the high excitation energies for the compound nuclei formed in these reactions, the effect of the large angular momenta on the cross sections and angular distributions of the evaporated alpha particles was found to be small. Similarly, the effect of the large angular momentum on the shape of the energy spectra is also small and can

[13] A. G. W. Cameron, Chalk River Laboratory Report CRP-690, AECL-433, December, 1958 (unpublished).

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

essentially be neglected. This neglect of the angular momentum can be justified for two reasons. First, as is seen from the angular distributions, the alpha particles are emitted approximately isotropically, so that, on the average, the angular momentum of the compound nucleus is about the same after the emission as it was before. Secondly, since the excitation energies are much greater than the spread in energy across the emitted alpha-particle energy spectrum, to a good approximation the temperatures of all the compound nuclei left after the evaporation are the same. By use of these two approximations the expressions[10] for the level density of a compound nucleus with angular momentum reduce to the form[10] for the level density of a compound nucleus with zero angular momentum.

Therefore, if the angular momentum is neglected, from the simple evaporation theory[10] the energy distribution of the evaporation alpha particles can be written as

$$N(E)\propto E\sigma_c(E)\omega(E_\alpha^*-E), \tag{1}$$

where E is the energy of the emitted particle, E_α^* is the maximum energy available to the emitted alpha particle, $\sigma_c(E)$ is the inverse cross section for the absorption of an alpha particle of energy E by the residual nucleus in an excited state of energy E_α^*-E, and $\omega(E_\alpha^*-E)$ is the level density in the residual nucleus. For a Fermi gas model of the nucleus the level density can be written as

$$\omega(E^*)\propto\frac{\exp[2(aE^*)^{\frac{1}{2}}]}{E^{*5/4}}. \tag{2}$$

Because of the exponential, for these large excitation energies the energy dependence in the denominator can be neglected, yielding the familiar expression,

$$\omega(E^*)\propto\exp[2(aE^*)^{\frac{1}{2}}]. \tag{3}$$

For these reactions E_α^* is much larger than the spread in energy across the spectrum of emitted particles. The emitted alpha particles have energies that are close to the Coulomb barrier energy so that

$$E_\alpha^*-B_\alpha\gg E-B_\alpha, \tag{4}$$

where B_α is the Coulomb barrier energy for an alpha particle entering the residual nucleus. Because of this the level density expression can be approximated by expanding the argument of the exponential in a Taylor series about $(E_\alpha^*-B_\alpha)$ and keeping only the first-order term. If this is done Eq. (1) becomes

$$N(E)\propto E\sigma_c(E)e^{-E/T}, \tag{5}$$

where

$$T=[(E_\alpha^*-B_\alpha)/a]^{\frac{1}{2}} \tag{6}$$

is the temperature of the residual nucleus. The Fermi gas model also predicts that the level density parameter a should be of the form

$$a=A/\epsilon,$$

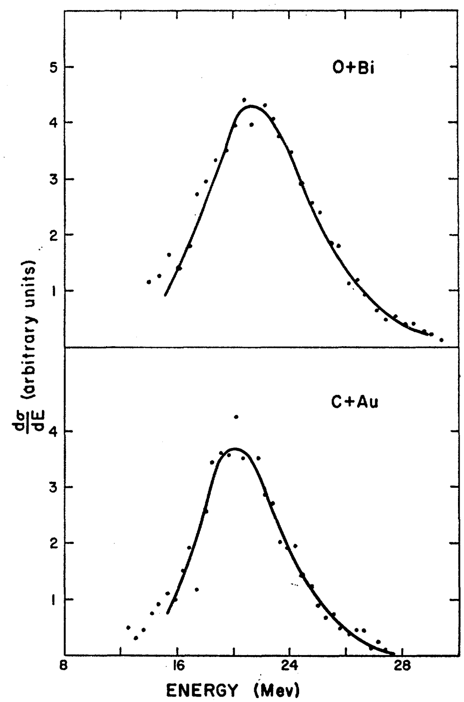

FIG. 8. The experimental center-of-mass energy spectra for evaporation alpha particles from the O+Bi and C+Au reactions at laboratory bombarding energies of 10.5 Mev/nucleon.

where ϵ is a constant. A survey of previous evaporation experiments indicates that ϵ should be about 10 Mev$\pm$20%.[10]

For several reasons it should be expected that the results obtained in these heavy-ion reactions would fit the predictions of the simple evaporation theory, based on a Fermi gas model of the nucleus. First the excitation energies involved are large so that the Fermi gas model should be appropriate. The strong dependence of the evaporation probability on the excitation energy should insure that most of the observed evaporation alpha particles come from compound nuclei with excitations near the maximum or, in other words, that the evaporation alpha particles are emitted very early in the deexcitation cascade. Also, the results presented above indicate that because of the heavy targets, any angular momentum effects should be small. Because of the high excitation energies and heavy targets, any shell effects should also be small so that the results obtained from the different reactions should be comparable, even though slightly different compound nuclei are involved.

Thus, the average temperatures of the residual compound nuclei can be obtained from the observed energy spectra for the evaporated alpha particles if the inverse cross sections are known. The inverse cross sections that were used in the analysis of the results were the total reaction cross sections for alpha particles that have been calculated by Igo,[15] using an optical model poten-

[15] G. Igo, Phys. Rev. 115, 1665 (1959).

tial that was determined from an analysis of alpha-particle elastic scattering data. For the reactions studied here the Coulomb barriers that are predicted by Igo, using this potential, agree with the peak energies for the observed center-of-mass energy spectra to the accuracy with which the peaks could be determined. The experimental center-of-mass energy spectra for the evaporation alpha particles from the C+Au and O+Bi reactions are shown in Fig. 8. The alpha-particle Coulomb barriers predicted by the optical model calculations are 20.7 and 21.9 Mev for the C+Au and O+Bi reactions, respectively.

The temperatures of the residual nuclei were determined for each reaction from the data taken at angles that were far enough back so that there was no significant contribution to the energy spectra from the direct alpha particles. This was done by analyzing only the energy spectra taken in the region where the laboratory angular distributions showed $d\sigma/d\Omega$ to be approximately constant. For each reaction, laboratory energy spectra were measured for several laboratory angles in this region. These spectra were each transformed to the center-of-mass system. Then for each spectrum $N(E)/E\sigma_c(E)$ was plotted versus E on a semilog scale using for $N(E)$ the experimental points of the energy spectra. Then for each reaction the average temperature

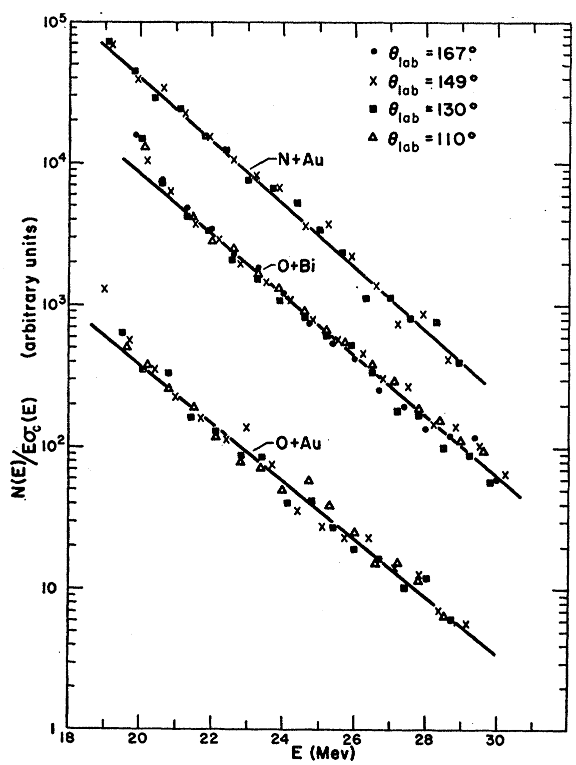

FIG. 9. The temperature plots obtained from the center-of-mass evaporation alpha-particle energy spectra for various reactions at bombarding energies of 10.5 Mev/nucleon. The data taken at various angles have been normalized so as to appear on a single plot for a given reaction.

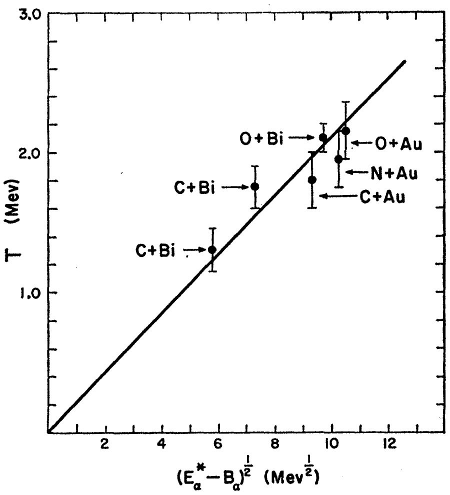

FIG. 10. The variation of the temperatures obtained from the evaporation alpha-particle energy spectra for the various reactions studied. The quantity E_α^* is the maximum energy available to an alpha particle evaporated from the initial full compound nucleus. B_α is the Coulomb barrier for alpha-particle emission from the initial full compound nucleus.

of the residual nucleus was determined from the best straight-line fit to the semilog plot for the data from all the appropriate angles. Some examples of these plots are shown in Fig. 9. In Fig. 9 the data taken at different angles have been normalized so that each reaction appears as a single plot. From these results it is seen that the shape of the center-of-mass evaporation energy spectrum is independent of angle as is expected from the evaporation theory. It can be seen from these results that the shapes of the evaporation energy spectra show the predicted $\exp(-E/T)$ dependence.

Figure 10 shows a plot of the experimental temperatures versus $(E_\alpha^* - B_\alpha)^{\frac{1}{2}}$. Within the accuracies of the points these results can be fitted by the expression given in Eq. (6). These results give a value for the average level density parameter, a, of 22 ± 2 Mev^{-1} or for a of the form $a=A/\epsilon$ a value for ϵ of 9.5 ± 1 Mev. This value for ϵ agrees well with previous experiments which have indicated that ϵ should be about 10 Mev$\pm20\%$.[10]

For the O+Au reaction, the temperature that was obtained was 2.15 ± 0.2 Mev. This agrees quite well with the value of 2.0 ± 0.3 Mev that was estimated for the initial temperature from the energy spectra of neutrons emitted from this reaction.[12]

D. Direct Alpha-Particle Energy Spectra

Experimental energy spectra for the direct alpha particles were determined by subtracting the contributions due to the evaporation alpha particles from the observed spectra. The evaporation alpha-particle energy spectra were determined from the data taken at far backward angles, as has been described previously. The direct alpha-particle spectra were found to be very broad and peaked at energies which were, in general,

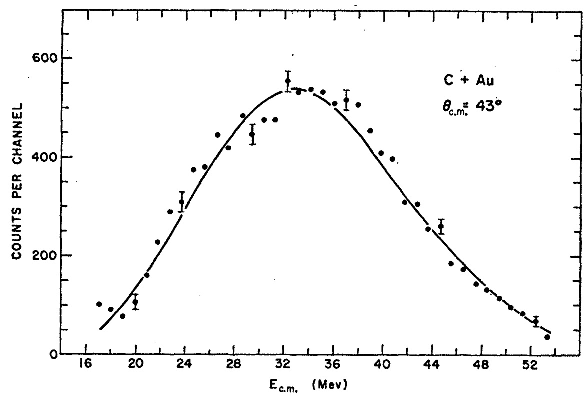

FIG. 11. The center-of-mass energy spectrum for direct alpha particles from the C+Au reaction at a c.m. angle of 43° for a bombarding energy of 10.5 Mev/nucleon. The solid curve is the calculated energy spectrum described in the text. The error bars shown are typical.

below the energy of an alpha particle that is traveling at the beam velocity. An example of the direct alpha-particle energy spectra is shown in Fig. 11. The peaks of the energy spectra were found to increase in energy with decreasing angle, and at small angles the peak energy approached the energy of an alpha particle that is emitted with the beam velocity. For example, for the full-energy C+Au reaction the velocity of an incident C^{12} nucleus was 10 Mev/nucleon in the center-of-mass system and the peaks of the direct alpha-particle energy spectra were found to decrease from 9.3 Mev/nucleon to 7.0 Mev/nucleon as the center-of-mass angle increased from 33° to 64°.

From these energy spectra and also from the angular distributions, which were found to be independent of the target but dependent on the type and velocity of the projectile, it appears that the major process involved in the emission of the direct alpha particles is the breakup of the incident projectile. If the alpha particles come from the projectile it is possible to consider the velocity spectrum of the outgoing alpha particles as arising from a vector addition of a velocity v to the velocity V of the incident projectile, yielding a resultant velocity V' for the outgoing alpha particle. If there is no strong interaction between the alpha particle and the target nuclei, then one might expect that the alpha particles should be distributed approximately isotropically in the rest system of the projectile. For a given $|v|$, if v/V is small, this corresponds to the alpha particles being emitted with approximately constant probability throughout a cone about the incident projectile direction. Then for a given distribution for the magnitudes of v, one can predict the energy spectrum of the outgoing alpha particles. Since the observed energy spectra were found to peak somewhat below the energy of an alpha particle with the beam velocity, this model would give an approximately correct description of the process if this lowering of the peak energy is due to an inelastic energy loss by the projectile before it breaks up. Then the decrease in peak energy with increasing angle would indicate that the average energy loss in inelastic processes increases with decreasing impact parameter, which is not unreasonable.

For a given $|v|$ it is easily shown that the resulting energy spectrum for the outgoing alpha particle is rectangular in shape and extends between maximum and minimum energies which are dependent on the ratio v/V. Using this it is then possible to predict the energy distribution of the outgoing alpha particles for any given distribution, $P(v)$, for the magnitudes of the velocity v of the alpha particle in the system of the projectile.

Using the above development, attempts were made to fit the observed energy spectra for the direct alpha particles from the C+Au reaction using several different types of velocity distributions $P(v)$. These velocity distributions were of the form $1/v$, $\exp(-v^2/v_0^2)$, $v\exp(-v/v_0)$, and $v^2\exp(-v^2/v_0^2)$. In order to fit the observed spectra, it was necessary to take for the incident projectile velocity V the velocity of an alpha particle at the peak of the observed energy spectrum. Since this velocity is somewhat below the incident beam velocity of 10 Mev/ nucleon, this procedure is essentially equivalent to assuming that the projectile loses some energy inelastically before breaking up as was pointed out previously. It was found that the best fit was obtained for a velocity distribution of the form

$$P(v)\propto v^2\exp(-v^2/v_0^2).$$

For this distribution the agreement between the calculated and the observed energy spectra was very good, as is shown for one case in Fig. 11. It was necessary to use different values for the projectile velocity V for the spectra taken at different angles because of the shift of the peak of the spectra with angle. However, it was found that within the experimental accuracies all of the spectra from the C+Au reaction could be fitted using the same value for v_0^2. For the C+Au spectra the value of v_0^2 needed was about 0.25 Mev/nucleon. If $P(v)$ is interpreted as the velocity distribution of alpha particles inside the carbon nucleus, then this would indicate that the average energy of an alpha particle in a carbon nucleus is about 1 Mev. However, it probably should not be expected that the $P(v)$ distribution obtained really quantitatively corresponds to the distribution of velocities for an alpha particle inside the projectile since the breakup appears to be caused by a nuclear interaction. Because of this, the observed $P(v)$ distribution probably results from combining the velocity distribution for alpha particles inside the projectile with some external velocity distribution characteristic of the breakup process. Therefore, not much can be learned from this one value for v_0^2, but it might be possible to obtain some information on the breakup process from the trend in the values of v_0^2 needed to fit the energy spectra of protons, alpha particles, and heavier particles from these breakup reactions, and also from the dependence of v_0^2 on the type of projectile. Unfortunately, there were not enough data taken in this experiment to study the dependence of v_0^2 on the type of particle emitted or the type of projectile involved in the breakup. It is, however, impressive that the energy spectra of the alpha particles emitted in these direct reactions can be fitted by these simple considerations using reasonable parameters. These results rather conclusively indicate that the direct alpha particles are coming from the projectile.

E. Direct Alpha-Particle Angular Distributions

For an alpha particle liberated by projectile breakup, if its energy when traveling at the beam velocity is much greater than its binding energy in the projectile, and if it does not interact strongly with the target nucleus, then one might expect it would continue approximately on the Rutherford trajectory of the incoming projectile. If the alpha particles do follow the original Rutherford trajectories then it is possible to correlate the angle of observation with a distance of closest approach, $r_{\min}$, for the nuclear collision from the following relationship:

$$r_{\min}=(Zze^2/2E_{\text{c.m.}})[\csc(\theta/2)+1],$$

where Z and z are the charges on the target and projectile, $E_{\text{c.m.}}$ is the center-of-mass energy of the projectile, and θ is the center-of-mass scattering angle.

By use of the above expression it is then possible to transform the angular distributions to the form $d\sigma/r_{\min}dr_{\min}$ versus $r_{\min}$. This quantity $d\sigma/r_{\min}dr_{\min}$ can be thought of as a measure of the probability of breakup at a given distance of closest approach. In this form the angular distributions should be approximately independent of the energy of the projectile. This type of analysis has been previously used in the analysis of the angular distributions obtained in heavy-ion experiments involving the transfer of a single nucleon between the projectile and the target nucleus.[16,17] For these single-nucleon transfer experiments this simple model is probably much more quantitatively applicable than for the emission of direct alpha particles, since the nuclear interaction involved is not as violent.

By use of the above relationships the experimental angular distributions, which were shown in Figs. 3 and 4, for the direct alpha particles were transformed to the form $d\sigma/r_{\min}dr_{\min}$ versus $r_{\min}$. These results are shown in Fig. 12. For the carbon-induced reactions this distribution peaks at about 12f which corresponds very closely to the sum of the radii for the projectile and the target nucleus if a radius parameter $r_0=1.5$f is used. Also within the experimental accuracies the results for the C+Bi reaction at the three bombarding energies used can all be fitted by the same curve apart from a cross-section normalization factor. The facts that the results show the probability of emission to be greatest for a grazing collision and that the variation with $r_{\min}$ is independent of the bombarding energy indicate the qualitative applicability of this simple model to this process. From the results shown in Fig. 12 it can be seen that the probability distribution for the oxygen- and nitrogen-induced reactions has a slightly different shape than for the carbon-induced reactions and peaks at about 10f. The significance, if any, of the peak being at a smaller value of $r_{\min}$ for the oxygen and nitrogen reactions is not clear. This difference might be related to the fact that for the carbon reactions it is possible that some of the alpha particles observed may come from the emission of Be^8 and its subsequent breakup into two alpha particles. This process might be expected to enhance the probability of alpha particles coming from collisions at larger impact parameters. This difference in peak positions could also indicate that it is more difficult to break off an alpha particle from an oxygen or nitrogen projectile than from a carbon projectile.

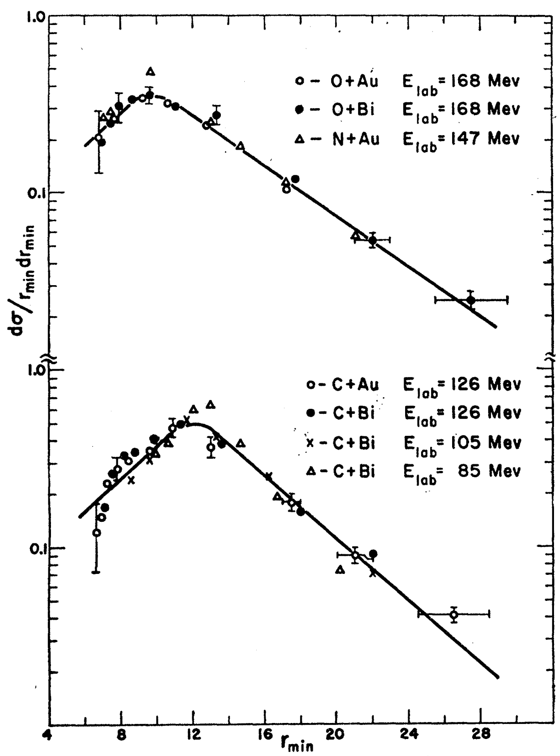

FIG. 12. The variation of the probability for the production of direct alpha particles with the classical distance of closest approach for the collision. The horizontal error bars represent the angular acceptance of the counter used in these experiments.

The distributions shown in Fig. 12 are much broader than those which are obtained in the single-nucleon transfer experiments.[16,17] However, because of the neglect of the effects of the breakup process and the interaction of the alpha particle with the target nucleus on

[16] J. A. McIntyre, T. L. Watts, and F. C. Jobes, Phys. Rev. **119**, 1331 (1960).
[17] R. Kaufman and R. Wolfgang, Phys. Rev. **121**, 206 (1961).

the trajectory of the emitted alpha particle, it is probably not possible to attach much physical significance to the detailed shape of the $d\sigma/r_{\min}dr_{\min}$ distributions. It is more reasonable to consider this type of analysis as a method for taking the gross Coulomb orbit effects out of the angular distributions. Then, from the variation of the $d\sigma/r_{\min}dr_{\min}$ distributions with the type of projectile and the type of particle emitted, one might hope to obtain some information on the characteristics of the breakup process. It should be remembered that this approach, in the simple form used here, is only applicable for the case where the projectile and the outgoing direct particle have the same values for Z/M.

F. Direct Alpha-Particle Cross Sections

The cross sections obtained for direct alpha-particle and proton emission have been listed previously in Table I. The large magnitudes of the cross sections observed indicate that the projectile breakup process involves predominantly a nuclear interaction rather than being a Coulomb breakup process. Calculations by Hansteen[18] on the cross sections expected for the Coulomb breakup of C^{12} projectiles indicate that for these reactions and energies the cross sections should be of the order of a few millibarns, but the observed cross sections are of the order of hundreds of millibarns. The fact that the cross sections for the production of direct alpha particles are much greater than for the production of direct protons for the carbon- and oxygen-induced reactions probably just reflects the alpha-particle structure of carbon and oxygen. If this is true then one might expect to observe more direct protons from a nitrogen-induced reaction. Unfortunately, at present no data are available on protons from a nitrogen reaction.

If an alpha particle is removed from a C^{12} nucleus leaving a Be^8 nucleus it might be expected that two more alpha particles would be observed from the decay of the Be^8 nucleus. However, if the breakup of the C^{12} nucleus occurs as a result of a close nuclear collision it is also possible for the Be^8 nucleus to be absorbed by the target nucleus, and as a result for only one alpha particle to be observed. Thus, the fact that the measured direct alpha-particle cross sections are about 50% greater for the carbon reactions than for the oxygen and nitrogen reactions could be due to more than one alpha particle being emitted in some of the C^{12} breakups and/or the probability of the breakup being different for C^{12} than for O^{16} and N^{14}.

For the C+Bi reactions the direct alpha-particle cross sections are found to increase rapidly with increasing bombarding energy. For the three energies studied, the dependence of the cross section on the bombarding energy is the same as that predicted by Kaufman and Wolfgang[17] from their grazing contact model for multinucleon transfer reactions.

[18] J. M. Hansteen, Nuclear Phys. **19**, 309 (1960).

There seems to be no correlation between the direct alpha cross sections and either the binding energy of an alpha particle in the projectile or the Q value for the (heavy ion, alpha particle) reactions. The cross sections which have been obtained by Kaufman and Wolfgang[17] for the multinucleon transfer reactions also do not show a correlation with the Q values for the reactions involved.

CONCLUSION

From these results and the previous fission results[1] it is possible to begin to understand some of the general characteristics of the reactions between heavy ions and heavy nuclei. For the reactions studied it is found that the major competing processes are fission, the evaporation of neutrons, and a direct process involving the breakup of the incident projectile. Because of the large Coulomb barriers it is found that the probability of evaporating charged particles is small.

These processes can be classified into the two general categories of compound system and direct processes. It appears that the competition between these two types of processes is dependent primarily on the impact parameters involved in the collisions. For small impact parameters it appears that a full compound nucleus is usually formed by the complete amalgamation of the projectile and the target nucleus. Then the subsequent de-excitation of this compound nucleus can be satisfactorily described in terms of the statistical compound nucleus theories. On the other hand, the direct projectile breakup reactions occur in interactions between the projectile and the surface of the target nucleus and, thus, involve the larger impact parameters. These reactions would then leave residual nuclei that are excited to energies considerably below the excitations involved in the full compound nucleus reactions.

The probability of evaporating alpha particles is found to increase rapidly with the excitation energy available in the compound system, so that it is reasonable to assume that the alpha particles are emitted from the full compound nucleus at the beginning of the de-excitation cascade. The evaporation alpha-particle energy spectra agree well with the predictions of the statistical evaporation theory based on a Fermi gas model of the nucleus. The temperatures which are obtained give a reasonable value for the average level density parameter for these compound nuclei and the temperature for the O+Au reaction agrees well with the value previously obtaihed from neutron measurements.[12] Because of the high excitation energies and the large moments of inertia for the compound nuclei it is found that the effect of the large angular momenta involved in these reactions on the evaporation angular distributions and the emission probabilities is small.

These results indicate that the major process involved in the emission of direct alpha particles is the breakup of the incident projectile. It is possible to fit the energy spectra by assuming that the alpha particles come from the incident projectiles and receive a small additional velocity component as a result of the breakup. An analysis of the angular distributions, assuming that the alpha particles follow the classical Coulomb orbits of the incoming projectiles, yields reasonable results and indicates that the direct alpha particles come primarily from the breakup of the incident projectile in a grazing collision with the target nucleus. The cross sections for the production of these direct alpha particles are found to increase rapidly with the bombarding energy and to be of the order of 25% to 35% of the estimated total reaction cross sections for the 10.5 Mev/nucleon bombarding energies.

The cross sections which have been obtained in this experiment and the previous fission experiment[1] exhibit several interesting properties. For the 10.5 Mev/nucleon bombarding energies it is found that to within the estimated accuracies the sum of the fission and the direct alpha-particle cross sections is equal to the estimated total reaction cross sections.[14] This then supports the previous conclusion[1] that for these energies the cross section not leading to fission is taken up by direct reactions. However, for the reduced-energy C+Bi reactions this sum is significantly less than the estimated total reaction cross section which gives some indication that here the probability of de-exciting the full compound nucleus by particle evaporation without fission occurring becomes appreciable. For the O+Au reaction where results are available[6] on the cross section for the emission of heavy direct particles it is found that this cross section is the same as the cross section for the emission of direct alpha particles to within the estimated uncertainties. For this case the sum of the fission and the total direct cross sections is 2.9 ± 0.3 b as compared to 2.3 b for the estimated total reaction cross section. This may indicate either that more than one particle is emitted in a typical breakup or that the residual compound nuclei left after the emission of a direct alpha particle have a large probability of fissioning. It is found, for the carbon- and oxygen-induced reactions, that the cross sections for the production of direct alpha particles are much greater than for the production of direct protons, which probably just reflects the alpha particle structure of carbon and oxygen. However, for the evaporation particles the cross sections are about 50% greater for protons than for alpha particles.

ACKNOWLEDGMENTS

We would like to thank Professor D. A. Bromley for many helpful discussions on the interpretation of the results. We gratefully acknowledge the assistance of J. C. Watson, C. R. Cothern, R. Ollerhead, and G. Seaman in obtaining the data presented herein.