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ANALYSIS OF SECONDARY PARTICLES RESULTING FROM
HIGH-ENERGY NUCLEAR BOMBARDMENT

Robert W. Deutsch
(Thesis)

July 1, 1953

Berkeley, California

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ANALYSIS OF SECONDARY PARTICLES RESULTING FROM HIGH-ENERGY NUCLEAR BOMBARDMENT

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ABSTRACT

Thin foils of Be, Al, Ni, Ag, Au, and U have been bombarded by an internal beam of 375 Mev alphas, 332 Mev protons, and 187 Mev deuterons. Secondary particles emerging from the disintegration of the nucleus at 0° to the incident beam direction are detected in nuclear emulsions located beneath the median plane of the 184-inch cyclotron. There are three specific positions for these emulsions corresponding to energies of the secondary protons and of alpha particles of approximately 6, 10, and 20 Mev. The angular distribution of secondary particles has also been measured for 240 Mev alpha bombardment of Be, Al, Ni and Ag. Here, secondary particles emitted at 0° , 45° , and 135° are detected in nuclear emulsions at positions for which the secondary proton and alpha energy is approximately 6 Mev. A secondary particle is identified by measurement of its radius of curvature upon entering the emulsion and its range and specific ionization in the emulsion. A considerable yield of hydrogen and helium isotopes as well as of particles of higher atomic number is found. The relative yields of the secondary protons and alpha particles for each element and for each bombardment are shown as a function of energy. The results are found to be consistent with the predictions of an evaporation model.

ANALYSIS OF SECONDARY PARTICLES RESULTING FROM HIGH-ENERGY NUCLEAR BOMBARDMENT

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I. INTRODUCTION

A. Interaction of High-Energy Nucleons with Nuclei

Nuclear disintegrations induced by nucleons having energies of the order of 100 Mev or greater are of a much more complex nature than those resulting from nucleons of lower energy.

A qualitative description for the interaction of high-energy nucleons with nuclei has been given by Serber.¹ Serber described the interaction by a two-step process*. In the first step, the incident nucleon transfers its energy to a few nucleons in the nucleus. Some of these nucleons immediately escape ($\sim 10^{-22}$ sec). The remainder interact quite strongly with remaining nucleons so that in a very short time (perhaps $\sim 10^{-21}$ sec) the nucleus can be considered to have come to an equilibrium temperature. In the second step the excited nucleus "boils off" particles; this process should be described by the usual evaporation model. The manner of excitation depends on the initial trajectory of the incident nucleon, e. g., if it passes near the edge of the nucleus it may interact with only one nucleon in the nucleus, or if it strikes the center of the nucleus it may make several collisions and transfer all its energy to the nucleons in the nucleus. Thus, depending on the number of nucleons that escape, the excitation of the resultant nucleus varies from zero energy to the full energy of the incident nucleon.

* Serber assumed that in a nucleon-nucleon collision only small momentum transfers are possible or that the incident nucleon lost only a fraction of its energy to the struck nucleon in the nucleus. The momentum transfer is $\sim \hbar/a$, where a is the range of nuclear forces corresponding to an energy of ~ 25 Mev. One arrives at this conclusion by using the Born approximation and considering only ordinary and exchange forces. However, p-p scattering experiments have since shown that large momentum transfers are possible. Serber's original arguments have been amended to take into account large momentum transfers.

A study of the residual nuclei²⁻⁶ resulting from the high-energy bombardment of nuclei, more commonly known as spallation reactions, has been made by Seaborg, Perlman, Helmholtz and their collaborators. The results of these experiments agree quite satisfactorily with the mechanism suggested by Serber. The residual nuclei may have lost anywhere from very few to forty or more nucleons.²

High-energy nuclear disintegrations initiated by cosmic rays⁷⁻¹⁴ or by artificial sources¹⁵⁻¹⁸ have also been studied extensively by the nuclear emulsion plate technique. Here, too, the experimental evidence favors a two-step process for the nucleon emission, although meson production tends to make the interpretation of results more difficult.

For nuclear disintegrations (stars) produced by cosmic rays, the tracks are divided into three classes⁸ according to their grain density as compared to minimum grain density, $g_{\min}$. Tracks less than $1.4 g_{\min}$ are known as "thin" tracks or shower particles. "Grey" tracks are defined as being produced by a particle of ionization between 1.4 and $6.8 g_{\min}$. All particles having a grain density greater than $6.8 g_{\min}$ are known as "black" tracks. The "thin" tracks are practically all mesons. The "grey" tracks have been shown to be composed of 72 percent protons, 22 percent deuterons and tritons, 6 percent mesons and a negligible proportion of charge 2 particles.¹⁴ The "black" tracks are composed primarily of hydrogen and helium isotopes. A proton having an energy between 30 and 500 Mev makes a grey track. Considering only stars which are produced from the heavy nuclei in emulsion (Ag, Br) and considering only nucleon components of the stars, one finds that the angular distribution suggests the mechanism for the production of grey and black tracks. The grey tracks tend to be directed in the direction of the primary particle.¹⁴ The black tracks, for protons less than 30 Mev and alphas less than 50 Mev, show an isotropic distribution.^{7,11,12} The grey tracks probably result from a direct nucleon-nucleon interaction since the angular distribution suggests a type of cascade process. The black tracks appear to result from the slower evaporation process.

Bernardini, et al.¹⁷ bombarded electron-sensitive plates with 300-400 Mev protons and neutrons and studied the resulting stars. They considered the resulting disintegration products which produce stars to be protons. The angular distribution of protons of greater than 30 Mev was similar to that found for grey tracks from cosmic ray work. However, in their work, the angular distribution of protons of energy less than 30 Mev was not found to be isotropic, in fact there was at least a 25 percent excess of protons in the forward direction.

In addition to the emission of individual nucleons and nuclear aggregates (2, 3, 4 nucleons), the ejection of larger fragments (Z from 3 to 10) is observed from both high-energy nuclear bombardment^{20, 21, 53} and cosmic-ray stars.²²⁻²⁶ Marquez and Perlman²¹ observed that when an element Z was bombarded with 335 Mev protons the element $Z + 3$ was formed in appreciable quantities. They interpreted this result as a second-order process in which the initial step is the production of lithium nuclei created with a very high energy, perhaps of the order of 80 Mev. Bombarding Cu with 340 Mev protons and examining the ranges of recoil fragments, Batzel and Seaborg⁵³ also found evidence for the production of fragments. There is rather confusing information concerning the production of fragments from cosmic-ray stars. Quite frequently stars are observed containing two or three fragments,^{22, 25} which is suggestive of occurrence of a fission process. On the other hand, the fact the high-energy fragments (greater than 4 Mev per nucleon) do not deviate greatly from the direction of the primary particle (the higher the energy of the fragment the less the deviation) suggests that they may be produced in a primary process.¹⁹

B. Theoretical Interpretations of Low-Energy Secondary Particles and Fragments Resulting from High-Energy Nuclear Disintegration

The evaporation model of the nucleus has had considerable success in predicting the energy spectrum, as well as the angular distribution, of low-energy secondary particles resulting from high-energy nuclear disintegrations. Historically, the evaporation model was developed by several authors.²⁷⁻²⁹ The energy distribution of the nuclear

particles emitted from a nucleus has been derived by Weisskopf.²⁹ He has shown that in a large nucleus at excitation energies that are high compared to the binding energy per nucleon, the level density is so large that the levels may be treated as a continuum, and a quantitative treatment of the disintegration along purely classical thermodynamical lines is possible.

The first application of this model for the purpose of analyzing the low-energy (less than 30 Mev) secondary particles resulting from cosmic ray stars was made by Bagge.^{30, 32} Bagge assumed a Fermi gas model of the nucleus and made allowance for cooling and barrier penetration. Unfortunately, Bagge was unable to achieve satisfactory agreement with experiment. However, it now appears that the experimental data could have been in error because of variable sensitivity of the emulsions used.¹⁹

Harding, et al.⁷ and Perkins¹¹ analyzed their data and used a model with the same refinements as were made by Bagge. They considered that all black tracks are produced in the evaporation process. Their observations extended over a wide range of excitation energies from 100 to 850 Mev. Even at these high excitation energies (larger than the total nuclear binding energy, ~700 Mev), the evaporation model very satisfactorily explained the energy and angular distribution of the protons. However, the alpha-particle energy and angular distribution do not agree with theory at high excitation energies. The number of low-energy alphas increases with excitation energy, and the most probable energy decreases with excitation energy. Bagge³² has postulated that a decrease in barrier height with increased excitation energy would account for this anomaly. Although the angular distribution for alphas of less than 50 Mev is isotropic,¹⁹ the angular distribution for higher energies is strongly collimated with the incident primary.¹⁹

Le Couteur³³ has extended the evaporation theory by considerations of the thermal expansion of the nucleus to take into account the decrease of potential barrier with increase of excitation energy, and the

effect of neutron excess. He has obtained energy distributions of the evaporated particles and has calculated the probability for the emission of the hydrogen and helium isotopes as a function of excitation energy. Le Couteur analyzed the data of Harding, et al.⁷ and Page⁹ and found the nuclear evaporation theory gave a consistent account of the main features of stars.

Bernardini, et al.³⁴ have formulated an entirely different approach to the analysis of low-energy secondary particles. From their experiment,¹⁷ in which they considered all the disintegration products to be protons, they found that angular distribution for protons of energy less than 30 Mev is not isotropic, but at least 25 percent of low-energy protons could be attributed to a knock-on process. They formulated a nucleonic cascade mechanism to explain their results. To treat the rather complicated cascade process, they employed a Monte Carlo method, which is a calculation basically similar to that which Goldberger had previously used to calculate the interaction of 90 Mev neutrons with lead nuclei.³⁵ An experimental check by Hadley and York³⁶ of Goldberger's calculation was not in very good agreement. Bernardini, et al. assume the nuclear excitation caused by nucleons trapped in the nucleus gives rise to evaporated particles which superimpose an isotropic component on the angular distribution. They achieve a satisfactory agreement with experiment, and the energy distribution of the knock-on protons appears to be similar to that of the evaporation spectrum. They attribute the disagreement with cosmic ray results to the difference in energy of the primary particle. According to their model, higher energy primaries induce large nucleonic cascades in which preference for the incoming direction is lost by many collisions, so that the protons with less than 30 Mev of energy may be expected to have an isotropic distribution.

The emission of fragments (Z from 3 to 10) has been described by Perkins.²⁵ He finds that the evaporation theory predicts a frequency of fragment emission much smaller than observed. Fujimoto and Yamaguchi³⁷ have accounted for these fragments by the fission

process. They believe that surface tension of the nucleus is decreased at high excitation energies so that energy can be concentrated in surface oscillations leading to fission. However, high-energy fragments (energies greater than 4 Mev per nucleon) are strongly collimated with the incident primary particle and cannot be explained by a fission process.¹⁹ Sorensen²⁶ has shown that they do not result from a direct knock-on by the primary particle. In order to explain these high-energy fragments, Perkins has postulated the existence of nucleon aggregates in the nucleus as well as long-range forces which can act over an assembly of nucleons without breaking up.

C. Purpose of the Experiment

As informative as the analysis of nuclear disintegrations in photographic emulsions may be, it still leaves much to be desired. Complications are introduced by the presence of gelatin (light nuclei) in the emulsion and, of course, events occurring in Ag and Br cannot be distinguished from each other, so that a mean mass has to be assumed. Also, the statistical error in identifying particles and their energies is large. On the other hand, the analysis by their radioactivity of nuclei resulting from high-energy bombardment gives very little information concerning the processes involved in proceeding from the initial to the resultant nucleus. Therefore, a controlled experiment to study the secondary particles produced from specific elements bombarded by particles of known energy should yield much information that is not now available. Barkas^{38, 52} has shown that this type of experiment is possible. The research reported herein is a continuation, in a systematic manner, of his original idea.

II. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

The entire experiment is performed beneath the circulating beam of the 184-inch cyclotron. The magnetic field of the cyclotron provides a means for analyzing the momentum of secondary particles emitted from an internal target. Nuclear track emulsions are employed to detect the secondary particles.

Two specific experimental arrangements have been constructed to utilize an existing cart, 40 in. by 20 in., which enters the cyclotron pressure chamber through an air lock. This cart can be placed in position beneath the circulating beam. One arrangement (Fig. 1) measures the relative abundances of secondary particles emitted at 0° for three different radius-of-curvature intervals. The other arrangement (Fig. 2) measures the relative abundances of secondary particles emitted at three different angles for one radius-of-curvature interval.

For both arrangements, the beam is clipped radially by a carbon block which is located on the opposite side of the cyclotron from the target. The beam is clipped at a radius two inches greater than the target radius. Vertical oscillations are also clipped by a copper block lowered into the beam so that the height of the beam at the target is largely confined to $3/4$ inch as determined by radioautographs of the target.

The nuclear-track plates which are used as detectors are 200 μ Ilford C2 emulsions. These emulsions are of moderate sensitivity, so as to obtain some ionization discrimination and yet to be able to see higher energy protons in the emulsion.

A. Momentum Distribution at 0° (Fig. 1)

Thin ribbon targets extending parallel to the magnetic field are placed with their smaller dimension perpendicular to the beam direction. These targets are exposed at a radius of 79 inches, corresponding to bombarding energies of protons of 332 Mev, deuterons of 187 Mev and alpha particles of 375 Mev. Secondary particles then spiral down into

MU 4051

Figure 1

nuclear emulsions which are placed at three specific positions along a radial line of the cyclotron. These positions correspond to radius of curvature intervals of 21-24.5 cm, 29-32.5 cm, and 42-46 cm. The nuclear-track plates are placed with emulsion upward in a plane parallel to the median plane of the cyclotron. The plates are 5-1/2 in. below the median plane for 21-24.5 cm and 29-32.5 cm positions, and 4-1/4 inches for the 42-46 cm position. The plates had to be raised for the 42-46 cm position so the orbits of the secondary particles could clear the edge of the cart. Shielding, of brass and copper, is placed around the plates to protect them against stray particles from the main beam and against neutrons from the target. Channels are built in the shielding so that particles with a plane projected angle of $\pm 10^\circ$ can enter the plates.

B. Angular Distribution (Fig. 2)

This apparatus detects particles which are emitted at angles of 0° , 45° and 135° to the incident-beam direction. In order to contain the orbits of secondary particles in regions of nearly constant magnetic field, the targets are exposed at a radius of 62 inches and mounted in the previously described manner. Thus the effective target thickness is $\sqrt{2}$ greater for the 45° and 135° position than for 0° . The radius-of-curvature interval for each position is 21-24.5 cm. At a 62-inch radius, the beam is only 2-7/8 inches above the plates. The elevation of the beam, coupled to the fact that only a limited amount of shielding could be placed around the plate, permitted only alpha bombardment as proton and deuteron bombardment blackened the plates with background tracks. The alpha energy at 62 inches is 240 Mev. The channels in the shielding permit particles with a plane projected angle of $0^\circ \pm 10^\circ$, $45^\circ \pm 10^\circ$, and $135^\circ \pm 10^\circ$ to enter the plates in each position.

C. Targets

The targets are thin foils prepared by commercial methods. The amount of contamination should be < 1 percent (no experimental verification was made of the purity of each element, however). Uranium

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Figure 2

is undoubtedly contaminated by the formation of an oxide which may be >1 percent. The target thickness is as follows:

Be	-	8.67	mg/cm ²
Al	-	1.67	"
Ni	-	8.10	"
Ag	-	12.8	"
Au	-	11.7	"
U	-	23.0	"

D. Microscope Measurements

The plates are scanned under ~1000x magnification. The position, range, plane projected angle, and charge of each track on a measured area of plate are recorded. Only tracks having the proper dip angle while entering the emulsion within $\pm 10^\circ$ of the mean plane projected angle for that plate are accepted. The ranges are measured by means of a calibrated reticule placed in the eyepiece of the microscope. However, some of the very long proton ranges (~1800 μ) were also measured by means of the microscope stage coordinates. The angles are measured within an accuracy of $\pm 1^\circ$ by a goniometer affixed to the eyepiece. For most positions, the charge-one secondary particles (hydrogen isotopes) can be separated by eye from the higher-charge secondary particles. The charge is recorded as one or greater than one. For those cases (to be discussed in the next section), where there is doubt concerning the charge, a measure of the specific ionization is made by recording the number of gaps in each track where there are no developed grains. Tracks were not recorded unless they were at least 9 microns long. This range was selected arbitrarily as a range that would not be overlooked by the observer, as well as being of sufficient length to get an accurate angle measurement.

III. METHOD OF ANALYSIS OF SECONDARY PARTICLES

A. Calculation of Range, Radius of Curvature and Acceptable Range Interval

In order to identify the secondary particles, one makes use of a set of curves in which the range in emulsion is calculated for each isotope and plotted as a function of radius of curvature (as in Fig. 4). In such a diagram each nuclear type falls on a characteristic locus. A point is plotted on the same graph, from an experimental determination of the range and radius of curvature. The position at which the point falls on the curve identifies the particle.

The calculation of the ranges involves first finding the H_p and, consequently, the energy of each particle. An expression for the H_p of a particle moving in the median plane of the nonuniform field of the cyclotron has been previously derived.³⁹ This expression, in which the trajectories are described in cylindrical coordinates (r, θ, z) and which is corrected for an orbit lying slightly outside the median plane, is:

$$H_p = \frac{\sec \gamma \int_{r_1}^{r_2} H(r) r dr}{r_1 \cos \lambda_1 - r_2 \cos \lambda_2} \quad (1)$$

where the subscripts refer to any point on the orbit, $\tan \lambda = 1/r dr/d\phi$ and γ is the angle of pitch of the spiral path. For the special case of an orbit whose initial and final trajectories intersect the same radial line (all positions in Fig. 1 and 0° position in Fig. 2), (1) reduces approximately (error < 0.1 percent) to:

$$H_p \approx \frac{\sec \beta \sec \gamma \int_{r_1}^{r_2} H(r) r dr}{r_1 + r_2} \quad (2)$$

where β is the plane projected angle measured with respect to a line perpendicular to the radial line. For cases of the 45° and 135° positions in Fig. 2, the expression is slightly more complicated. The

magnetic field of the cyclotron has been measured (relative field values are accurate to ~ 0.02 percent but the absolute value of the field could be off by as much as 0.1 percent) and $H\rho$ calculated by a numerical integration. The relativistic expression for the kinetic energy of a secondary particle is:

$$T = \sqrt{Z^2 (e/c)^2 H^2 \rho^2 + M^2 c^4} - Mc^2 \quad (3)$$

where Z is the number of units of charge carried by the particle, e/c is the electronic charge in emu and M is the ionic mass.

Table I shows the secondary particles considered and their mean energies in each plate not corrected for energy loss in the target. Carbon is the highest atomic number considered, because the range energy curves have not been verified for higher atomic number and because the resolution becomes very poor.

Knowing the energies, we find the ranges in emulsion of the hydrogen and helium isotopes by using the published data of J. J. Wilkins.⁴⁰ For the heavy secondary particles, the ranges are found by using the range energy curves for the alpha particles and making use of an empirical expression which describes the range extension introduced by electron pick-up.⁴¹

Fig. 3 shows a diagram of an orbit traveled by a particle upon leaving the target. From simple geometrical considerations and assuming a uniform magnetic field, the radius of curvature, ρ , is

$$\rho = \rho_H \sec \gamma = \frac{d}{2} \sec \beta \sqrt{1 + \frac{4h^2 \cos^2 \beta}{(\pi \pm 2\beta)^2 d^2}} \quad (4)$$

where ρ_H is the horizontal projection of ρ , γ is the angle of pitch ($\tan^{-1} h/\pi\rho_H$), d is the distance from the target measured along the x axis at which a particle enters the emulsion, h is the height of the

MEAN ENERGY OF SECONDARY PARTICLES

Radius of Curvature Interval	42-46 cm	29-32.5 cm	21-24.5 cm
H ¹	18.5	9.1	5.0
H ²	9.3	4.6	2.5
H ³	6.2	3.0	1.7
He ³	24.9	12.2	6.6
He ⁴	18.8	9.2	5.0
He ⁶	12.5	6.1	3.3
He ⁷	10.7	5.2	2.9
Li ⁶	28.2	13.8	7.5
Li ⁷	24.2	11.8	6.4
Li ⁸	21.2	10.3	5.6
Li ⁹	18.8	9.2	5.0
Be ⁷	43.0	21.0	11.4
Be ⁹	33.0	16.3	8.9
Be ¹⁰	30.1	14.7	8.0
B ⁸	58.8	28.7	15.6
B ¹⁰	47.0	22.9	12.5
B ¹¹	42.7	20.8	11.3
B ¹²	37.2	19.1	10.4
C ¹⁰	67.7	33.0	18.0
C ¹¹	61.5	30.0	16.3
C ¹²	56.4	27.5	15.0
C ¹³	52.1	25.4	13.9
C ¹⁴	48.3	23.7	12.9

MU-4560

Table I

MU-5505

Figure 3

beam above the emulsion, and β is the plane projected angle (whose sign depends on the direction of the particle entering the plate). We can correct ρ by taking into account the nonuniformity of the field. That is, more exactly, $\rho = (H\rho)/\bar{H}$ where $H\rho$ is determined from (2) and $\bar{H}$ is the mean value of the magnetic field for the orbit. The values for ρ determined by the two methods differ by $< 0.002 \rho$.

The calculated range vs. ρ curve gives a characteristic locus for each nuclear type. However, this calculation has to be verified experimentally because there is possible variation in the stopping power of the emulsion and error in the determination of the absolute value of the magnetic field. An experimental check was made by measuring the range energy curve for alpha particles. There was agreement to better than 1 percent for the calculated curves in all plate positions.

In order to determine how far from a calculated locus the range of a particle may fall and still be included as belonging to that locus, the range straggle was measured for the hydrogen and helium isotopes. The standard deviation was found to be nearly constant for all ranges and to be 3 percent or less of the range. (The range straggle includes the usual Bohr straggling, the effect of the finite width of the target, and observer errors.) The acceptable band width for each locus was taken as $\pm 2\frac{1}{2}$ standard deviations or $\pm 7\frac{1}{2}$ percent of the range.

Protons have by far the longest range in each position and also undergo the most scattering. They could not be measured to the same accuracy as the other particles without consuming an inordinate amount of time. The band width for protons was widened to ± 10 percent to allow for less accurate measurements. Protons in the 42-46 cm position, which have a range of 1800μ , frequently (~ 30 percent) scatter out of the plate before coming to the end of their range.

In order to determine the number of protons that come from the target, a plot is made of the protons that leave the emulsion. The protons that have too long a range to have come from the target determine

the background. It is found that the background protons constitute about 30 percent of the protons leaving the plate.

There is some overlap of ranges for the hydrogen and helium isotopes, notably H^2 and He^3 , for all positions. Identification of such tracks was made by gap count. If G is the number of gaps in a residual range R , and M is the ionic atomic weight, then $G/M = f(R/M)$ where $f(R/M)$ is the same function of (R/M) for all isotopes of an element. Curves of $f(R/M)$ prepared from tracks of all isotopes which have been identified provided means for separating completely H^2 and He^3 . There is also a slight overlap between H^3 and He^4 in the 21-24.5 cm position, and it was necessary to narrow the acceptable band width to 6 percent of the range for this case, as the tracks for these particles are too dense to separate by gap count.

Only a few of the heavier particles can be identified individually. Li^8 and B^8 can always be distinguished from others by the characteristic hammer at the ends of their tracks and from each other by their ranges. Li^7 can be separated only in the 42-46 cm position. Li^6 and Be^7 together form a common locus which is separable in each position, although there is possible contamination with carbon isotopes in the 21-24.5 cm position. For these particles also, a $\pm 7-1/2$ percent band width was taken, except for Li^6 and Be^7 in the 21-24.5 cm position, where the band width was 6 percent of the range.

Figure 4 shows the calculated loci for the secondary particles that could be identified individually, together with a representative sample of experimentally determined points for one of the bombardments using the 0° apparatus.

As for the remaining secondary particles listed in Table I, there is an overlap of ranges, and separation was therefore attempted by grouping the calculated loci together wherever possible. The groups chosen are shown in the table of results. They were chosen arbitrarily and could very well overlap. The small number of these particles found

REPRESENTATIVE SAMPLE OF SECONDARY PARTICLES RESULTING
FROM ALPHA BOMBARDMENT OF Be.

MU-5206

Figure 4

does not justify going into greater detail. Only tracks which were greater than 9μ were accepted. All tracks that had a range greater than 9μ but were still too short to fall on any calculated locus were listed in the "not classified" group. For the 29-32.5 cm and the 42-46 cm positions, the members of these groups are fission fragments or members of the other groups that are not fully stripped of electrons when they leave the target. The resolution decreases in going from the 42-46 cm plate to the 21-24.5 cm plate. In the latter position, Li^6 and Be^7 were the only heavy particles that could be separated; all the rest fell so close together that it was not even possible to separate by groups, and they were all listed in the "not classified" group for this position.

B. Background

The general background is very definitely a function of the element used as target. Unfortunately, it is not possible to measure the background experimentally by removing the target. The target acts as a beam clipper as well as a neutron source, so that conditions are not comparable when the target is absent. Since the same amount of shielding for the plates is used with each kind of bombarding particle, the general background may also be expected to be a function of the range of the bombarding particle in the shielding. The background resulting from alpha and deuteron bombardment is very much less than the background resulting from proton bombardment. Nevertheless, the background tracks, which arise principally from the scattered beam and neutrons striking the cart and shielding, are not a serious problem. The angle criteria (accepting only tracks of the proper projected and dip angles) rule out most of the background. With the exception of protons, practically all the secondary particles (~98 percent) fall within the calculated range intervals. The situation for the heavy-particle groups and "not classified" group is slightly ambiguous, as there is no range criterion to eliminate background here. However, only tracks which can be observed to have a charge of two or greater are included in this group

and this type of background (charge 2 or greater) is believed to be small. Almost all the background tracks which satisfy the angle criteria and do not fall within calculated range intervals are protons, and most of these protons fall well outside the calculated range interval.

C. Solid Angle Factor and Reduction of Data

In making a comparison of the data from different plates, one must take into account the solid angle subtended by each plate. It is necessary to transform the plate coordinates (x, y, β) into the target coordinates (ρ, θ, ϕ) . That is, it is necessary to transform the number of tracks found per unit area per angular interval on the plate into the number of particles per unit solid angle per unit radius-of-curvature interval leaving the target. This transformation⁴² is accomplished by means of a Jacobian, J , such that:

$$\frac{\Delta N}{\Delta \rho \Delta \omega} = \frac{\Delta N}{\Delta \rho \Delta \cos \theta \Delta \phi} = J \left(\begin{matrix} x_1 y_1 \beta \\ \rho, \theta, \phi \end{matrix} \right) \frac{\Delta N}{\Delta x \Delta y \Delta \beta} \quad (5)$$

The value of the Jacobian is:

$$|J| = \frac{2h}{\cos^2 \theta} \sin^2 \frac{h}{2\rho \cos \theta}.$$

For the special case of 180° focusing, as we have in the two experimental arrangements, the Jacobian reduces to $2h[1 + (\pi \rho_H/h)^2]$, where h is the height of the beam above the plate and ρ_H is the horizontal projection of the radius of curvature. This Jacobian is needed as a weighting factor to reduce the data for the apparatus shown in Fig. 1. However, for the angular distribution, Fig. 2, the Jacobian is the same for each position, as ρ_H and h are the same in each position.

Finally, expression (5) is transformed into a function of the energy by using a nonrelativistic relationship between energy and momentum, such that:

$$\frac{\Delta N}{\Delta E \Delta \omega} = \frac{\rho}{2E} \frac{\Delta N}{\Delta \rho \Delta \omega} \quad (6)$$

IV. EXPERIMENTAL RESULTS

A. Momentum Distribution at 0°

Table II gives the abundance distribution of secondary particles obtained for 375 Mev alpha bombardment. Tables III and IV give similar results found for 332 Mev proton and 187 Mev deuteron bombardments. In these tables, each element has been normalized to one hundred percent for the number of particles found per unit solid angle per unit radius-of-curvature interval. The numbers not in brackets are the percent values of each secondary particle found. The figure in brackets are the actual numbers of tracks found. The method for reducing the data to this form has been described in Section III-C.

As can be seen from the results, the secondary particles are mainly confined to the hydrogen and helium isotopes, although there is an appreciable amount of higher atomic number secondary particles (fragments) found. In particular, the statistics are fair (usually better than 10 percent) only for protons and alphas. Figures 5-10 show the relative yield of the secondary protons and alphas for each element and for each bombardment as a function of energy. Since only relative yields have been measured, it is not possible to compare different bombardments of the same element directly, since a knowledge of the absolute yield would be required. The points in these plots have been arbitrarily connected by straight lines. The transformation from a momentum to an energy distribution is obtained by means of equation (6) in Section III-C. In these plots, the errors shown for the number of particles found are statistical errors expressed in standard deviations. The energy resolution for each element shown is found by combining the energy spread determined by scanning a finite length of plate with the loss of energy by ionization caused by the finite thickness of the target. Since the yield of particles in the energy region being studied is strongly energy-dependent, the energy resolution shown for each point is the entire energy interval considered. If a more exact fold is performed and the energy resolution is

RADIUS OF CURVATURE INTERVAL																		
42-46 cm							29-32.5 cm						21-24.5 cm					
Element	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U
H ¹	10.92 (163)	12.10 (199)	13.36 (239)	17.37 (194)	29.62 (178)	28.74 (204)	8.36 (119)	13.57 (214)	26.88 (401)	38.56 (499)	19.59 (402)	9.79 (271)	6.50 (125)	14.82 (276)	31.16 (491)	15.90 (500)	1.67 (176)	2.45 (137)
H ²	3.62 (54)	2.43 (40)	2.63 (47)	3.40 (38)	3.16 (19)	2.26 (16)	3.34 (56)	1.97 (31)	0.87 (13)	0.15 (2)	0.09 (2)	0.33 (9)	2.08 (43)	0.65 (12)	0.19 (3)	0.36 (2)	0.14 (16)	0.25 (14)
H ³	2.75 (41)	0.48 (8)	0.34 (6)	0.09 (1)	0.17 (1)	0.42 (3)	2.32 (33)	0.17 (3)	0.34 (5)	0.15 (2)	0.09 (2)	0.25 (7)	1.51 (29)	0.43 (8)		0.03 (1)	0.08 (9)	0.15 (8)
He ³	2.68 (40)	1.46 (24)	1.29 (23)	1.07 (12)	1.16 (7)	1.13 (6)	4.29 (61)	1.33 (21)	1.01 (15)	0.08 (1)	0.15 (3)	0.47 (13)	2.76 (53)	0.59 (11)	0.38 (6)	0.36 (2)	0.17 (20)	3.27 (15)
He ⁴	10.52 (157)	9.57 (159)	7.88 (141)	17.46 (195)	28.29 (170)	18.60 (132)	17.13 (273)	14.97 (236)	8.51 (127)	2.24 (29)	1.17 (24)	3.87 (107)	12.59 (242)	11.70 (218)	2.22 (35)	0.25 (8)	0.49 (58)	4.01 (224)
Li ⁶ , Be ⁷	0.74 (11)	0.42 (7)	0.50 (9)	0.63 (7)	1.50 (9)	1.55 (11)	0.63 (9)	1.14 (18)	0.47 (7)		0.34 (7)	0.47 (13)	0.93 (16)	0.48 (9)	0.19 (3)		0.43 (5)	0.38 (21)
Li ⁷	0.33 (5)	0.48 (8)	0.34 (6)	0.27 (3)	0.83 (5)	0.28 (2)												
Li ⁸	0.37 (1)					0.14 (1)	0.28 (4)						0.16 (3)					0.32 (1)
B ⁸	0.37 (1)	0.36 (1)												0.05 (1)				
I	0.27 (4)	0.42 (7)	0.06 (1)	0.27 (3)	0.17 (1)		0.77 (11)	1.46 (23)	0.47 (7)	0.38 (5)	0.68 (14)	0.43 (12)						
II	0.37 (1)	0.18 (3)	0.36 (1)	0.09 (1)	0.17 (1)	0.42 (3)	0.21 (3)	1.27 (20)	0.14 (2)	0.08 (1)	0.39 (2)	0.32 (9)						
III		0.12 (2)	0.36 (1)	0.18 (2)		0.71 (5)												
Not Classified	0.13 (2)	0.61 (10)	0.22 (4)	0.81 (9)	8.15 (49)	16.91 (120)	0.07 (1)	3.30 (52)	0.14 (2)	0.23 (3)	1.27 (26)	4.05 (112)	1.35 (26)	3.60 (67)	0.32 (5)	0.18 (6)	1.31 (37)	1.36 (76)
	I - He ⁶ , Be ⁹ , B ¹⁰ , C ¹¹ II - Be ¹⁰ , B ¹¹ , C ¹² , C ¹³ III - He ⁷ , Li ⁹ , B ¹² , C ¹⁴						I - He ⁶ , Li ⁷ , Be ⁹ , Be ¹⁰ , B ¹⁰ , B ¹¹ , C ¹¹ , C ¹² , C ¹³ II - He ⁷ , Li ⁹ , B ¹² , C ¹⁴											

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375 MEV ALPHA BOMBARDMENT

Table II

332 MEV PROTON BOMBARDMENT
RADIUS OF CURVATURE INTERVAL

Element	42-46 cm						29-32.5 cm						21-24.5 cm					
	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U
H ¹	7.65 (166)	3.49 (160)	10.48 (230)	17.36 (206)	27.26 (177)	27.63 (312)	7.63 (143)	15.56 (255)	28.40 (403)	35.76 (473)	26.77 (349)	7.76 (264)	7.96 (80)	25.51 (166)	37.58 (257)	18.27 (325)	1.87 (87)	2.08 (117)
H ²	3.87 (84)	3.11 (59)	2.23 (49)	4.30 (57)	3.80 (23)	2.56 (27)	4.74 (67)	2.91 (33)	1.97 (14)	3.45 (6)	1.23 (3)	3.37 (13)	3.11 (25)	1.23 (8)	0.29 (2)		0.04 (2)	0.27 (15)
H ³	2.90 (63)	0.68 (13)	0.41 (9)	1.07 (13)	0.33 (2)	0.57 (6)	3.65 (53)	0.47 (8)		1.07 (1)	1.15 (2)	0.21 (6)	2.99 (24)	0.77 (5)	0.14 (1)			0.11 (6)
He ³	1.52 (33)	1.26 (24)	0.50 (11)	1.09 (13)	0.39 (6)	0.67 (7)	4.47 (65)	1.28 (21)	0.63 (9)	1.52 (7)	0.15 (2)	0.41 (11)	3.24 (26)	0.31 (2)	0.14 (1)	0.06 (1)	0.02 (1)	0.11 (6)
He ⁴	5.63 (122)	6.32 (120)	4.15 (31)	12.88 (153)	26.12 (158)	17.25 (182)	13.78 (273)	13.54 (222)	10.01 (142)	5.60 (74)	0.77 (10)	2.21 (6)	13.33 (107)	13.37 (87)	2.63 (18)	0.17 (3)	0.34 (16)	6.81 (383)
Li ⁶ , Be ⁷	0.46 (10)	0.32 (6)	0.05 (1)		0.56 (4)	0.47 (5)	0.37 (13)	0.43 (7)	0.35 (5)	0.07 (1)	0.39 (5)	0.25 (7)	0.75 (6)	0.31 (2)			0.02 (1)	0.08 (2)
Li ⁷	0.23 (5)	0.37 (7)	0.09 (2)	0.17 (2)	0.17 (1)	0.57 (6)												
Li ⁸	0.05 (1)	0.15 (1)	0.05 (1)	0.09 (1)														
B ⁸																		
I	0.05 (1)		0.07 (2)		0.33 (2)	0.19 (2)	0.67 (13)	0.79 (13)	0.28 (4)	0.14 (2)	0.69 (3)	0.22 (6)						
II		0.11 (2)	0.05 (1)		0.62 (5)	0.19 (2)	0.21 (3)	0.43 (7)	0.14 (2)		0.25 (3)	0.25 (7)						
III	0.09 (2)			0.17 (2)	0.50 (3)	0.19 (2)												
Not Classified	0.51 (11)	0.77 (15)	0.32 (7)	1.09 (13)	4.30 (26)	15.35 (168)	0.07 (1)	0.55 (9)		0.07 (1)	0.69 (9)	8.06 (218)	0.12 (1)	0.22 (6)		0.06 (1)	0.13 (6)	0.50 (28)
	I - He ⁶ , Be ⁷ , B ¹⁰ , C ¹¹ II - Be ¹⁰ , B ¹¹ , C ¹² , C ¹³ III - He ⁷ , Li ⁹ , B ¹² , C ¹⁴						I - He ⁶ , Li ⁷ , Be ⁷ , Be ¹⁰ , B ¹¹ , C ¹¹ , C ¹² , C ¹³ II - He ⁷ , Li ⁹ , B ¹² , C ¹⁴											

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Table III

187 MEV DEUTERON BOMBARDMENT

RADIUS OF CURVATURE INTERVAL

Element	42-46 cm						27-32.5 cm						21-24.5 cm					
	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U	Be	Al	Ni	Ag	Au	U
H ¹	12.22 (76)	14.10 (146)	9.47 (132)	15.63 (104)	51.50 (138)	34.61 (109)	7.47 (61)	16.02 (120)	27.36 (183)	45.03 (241)	20.16 (200)	8.30 (105)	10.82 (87)	22.21 (165)	40.11 (256)	16.74 (260)	1.45 (136)	2.26 (109)
H ²	4.84 (38)	3.38 (35)	1.94 (27)	3.77 (26)	1.86 (5)	2.54 (8)	3.92 (32)	1.86 (14)	1.05 (7)			0.76 (9)	2.74 (22)	0.40 (3)		0.12 (2)	0.05 (5)	0.11 (5)
H ³	2.67 (21)	0.58 (6)	0.07 (1)	1.05 (7)		0.32 (1)	1.36 (16)	0.26 (2)		0.19 (1)	0.21 (2)	0.42 (5)	1.37 (11)	0.27 (2)		0.06 (1)	0.31 (1)	0.06 (3)
He ³	3.31 (26)	0.96 (10)	0.86 (12)	0.60 (4)	0.37 (1)	0.95 (3)	2.81 (23)	0.26 (2)	0.30 (6)	0.37 (2)		0.34 (4)	2.74 (22)	0.94 (7)	0.31 (2)		0.04 (3)	0.25 (12)
He ⁴	8.40 (66)	6.37 (66)	3.95 (55)	12.62 (84)	22.77 (61)	3.84 (31)	14.32 (117)	15.49 (116)	10.91 (73)	2.80 (15)	0.21 (2)	2.96 (35)	14.68 (118)	12.25 (71)	2.04 (13)	0.19 (3)	0.23 (21)	2.07 (100)
Li ⁶ , Be ⁷	0.64 (5)		0.22 (3)	0.15 (1)		0.64 (2)	1.43 (12)	0.26 (2)	0.30 (2)		0.10 (1)	0.16 (2)	0.62 (5)	0.40 (3)			0.05 (5)	0.16 (8)
Li ⁷	0.25 (2)		0.07 (1)															
Li ⁸							0.24 (2)						0.25 (2)					
B ⁸																		
I	0.25 (2)		0.07 (1)	0.15 (1)			0.36 (6)	1.32 (10)	0.15 (1)	0.19 (1)		0.42 (5)						
II					0.37 (1)			0.53 (4)		0.19 (1)		0.09 (1)						
III																		
Not Classified	0.11 (1)	0.07 (1)			0.37 (1)	24.77 (78)	0.24 (2)	0.80 (6)			0.21 (2)	7.04 (83)	0.75 (6)	1.21 (9)	0.16 (1)		0.05 (4)	0.31 (15)
	I - He ⁶ , Be ³ , B ¹⁰ , C ¹¹ II - Be ¹⁰ , B ¹¹ , C ¹² , C ¹³ III - He ⁷ , Li ³ , B ¹² , C ¹⁴						I - He ⁶ , Li ⁷ , Be ⁹ , Be ¹⁰ , B ¹⁰ , B ¹¹ , C ¹¹ , C ¹² , C ¹³ II - He ⁷ , Li ⁹ , B ¹² , C ¹⁴											

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Table IV

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Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

U

Figure 10

expressed in standard deviations, only the energy spread for the alphas in the low-energy position would be smaller by a significant amount. The ionization loss for protons and alphas in Be, Al and Ag targets was found directly from Aron's range-energy curves.⁴⁷ The ionization loss in the Ni, Au, and U targets was found by extrapolating the results for Cu and Pb, respectively, considering the change in electron density.

Table V and Fig. 11 give the results of an alpha-proton ratio as a function of atomic number for the three energies considered and for each bombardment.

B. Angular Distribution

Tables VI to IX give the results obtained for Be, Al, Ni, and Ag for 240 Mev alpha bombardment. In these tables, each element has been normalized to one hundred percent for the number of particles found per unit solid angle per unit radius-of-curvature interval. The numbers not in brackets are the percent values for each secondary particle found. The numbers in brackets are the actual numbers of tracks found. Figure 12 is a plot of the relative yields of protons and alpha particles (the errors shown are statistical errors). The energies of the protons considered are 5.5 ± 0.6 Mev, while the energies of the alpha particles are 6.8 ± 1.9 Mev.

The results for Au and U have not been included. The results for different exposures for these elements were inconsistent and not very reproducible. However, the yields from these bombardments were quite low, the flux of secondary particles being less than one hundredth as much, for the same bombarding time, as for the other elements. The fact that the yields are low for Au and U is not surprising, since the energies of the secondary particles are well below the coulomb barrier for these elements. For extremely low yields, it is to be expected that any background effects, such as stray particles striking the cart and shielding and being scattered into the plates or producing secondary particles which enter the plates and satisfy the angular and range criteria, will be greatly

Figure 11

$$\frac{\text{He}^4}{\text{H}^1} \text{ Ratio}$$

TABLE V

	Alpha Bombardment (375 Mev)	Proton Bombardment (332 Mev)	Deuteron Bombardment (187 Mev)
Radius of Curvature Interval 42-46 cm			
Be	0.96 ± 0.11	0.73 ± 0.09	0.69 ± 0.12
Al	0.80 ± 0.08	0.67 ± 0.08	0.45 ± 0.07
Ni	0.59 ± 0.06	0.40 ± 0.05	0.42 ± 0.07
Ag	1.01 ± 0.10	0.74 ± 0.08	0.81 ± 0.09
Au	0.96 ± 0.10	0.89 ± 0.10	0.44 ± 0.07
U	0.65 ± 0.07	0.58 ± 0.06	0.28 ± 0.06
Radius of Curvature Interval 29-32.5 cm			
Be	2.29 ± 0.25	1.91 ± 0.20	1.92 ± 0.30
Al	1.10 ± 0.10	0.87 ± 0.08	0.97 ± 0.13
Ni	0.32 ± 0.03	0.35 ± 0.04	0.40 ± 0.06
Ag	0.06 ± 0.01	0.16 ± 0.02	0.06 ± 0.02
Au	0.06 ± 0.01	0.03 ± 0.01	0.01 ± 0.01
U	0.39 ± 0.05	0.23 ± 0.04	0.33 ± 0.06
Radius of Curvature Interval 21-24.5 cm			
Be	1.94 ± 0.21	1.34 ± 0.20	1.36 ± 0.19
Al	0.79 ± 0.07	0.52 ± 0.07	0.55 ± 0.09
Ni	0.07 ± 0.01	0.07 ± 0.02	0.05 ± 0.02
Ag	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.01
Au	0.30 ± 0.05	0.18 ± 0.05	0.16 ± 0.04
U	1.64 ± 0.19	3.27 ± 0.32	0.92 ± 0.13

TABLE VI

Be

Angular Position	0° Position	45° Position	135° Position
H ¹	13.67 (210)	8.80 (252)	2.95 (324)
H ²	4.30 (66)	2.27 (65)	0.77 (83)
H ³	2.61 (40)	2.41 (69)	0.57 (63)
He ³	4.43 (68)	2.55 (73)	0.62 (68)
He ⁴	24.42 (375)	16.14 (462)	2.49 (273)
Li ⁶ , Be ⁷	2.67 (41)	2.65 (76)	0.21 (23)
Li ⁸	0.13 (2)	0.10 (3)	
Not Classified	2.67 (41)	2.51 (72)	0.04 (4)

TABLE VII

Al

Angular Position	0° Position	45° Position	135° Position
H ¹	20.65 (198)	19.75 (194)	9.18 (229)
H ²	0.66 (7)	1.04 (8)	0.62 (14)
H ³	0.63 (6)	1.31 (13)	0.44 (11)
He ³	0.53 (5)	0.69 (7)	0.44 (11)
He ⁴	15.77 (152)	12.58 (122)	4.97 (127)
Li ⁶ , Be ⁷	0.59 (6)	2.05 (19)	0.11 (3)
Not Classified	5.38 (51)	2.51 (28)	0.11 (3)

TABLE VIII

Ni

Angular Position	0° Position	45° Position	135° Position
H ¹	36.34 (267)	27.29 (241)	23.64 (225)
H ²	0.27 (2)	0.33 (3)	0.31 (3)
H ³	0.13 (1)	0.33 (3)	0.42 (4)
He ³	0.27 (2)	0.33 (3)	0.31 (3)
He ⁴	1.91 (14)	3.05 (27)	4.20 (40)
Li ⁶ , Be ⁷		0.33 (3)	
Li ⁸	0.13 (1)		
Not Classified	0.27 (2)	0.11 (1)	

TABLE IX

Ag

Angular Position	0° Position	45° Position	135° Position
H ¹	27.90 (259)	26.88 (217)	35.09 (236)
H ²	0.11 (1)	0.12 (1)	0.15 (1)
H ³	0.22 (2)	0.37 (3)	0.15 (1)
He ³	0.11 (1)	0.12 (1)	0.15 (1)
He ⁴	0.32 (3)	2.73 (22)	3.86 (26)
Li ⁶ , Be ⁷	0.11 (1)	0.99 (8)	0.15 (1)
Not Classified	0.11 (1)	0.37 (3)	

ANGULAR DISTRIBUTION RESULTING FROM 240 MEV ALPHA BOMBARDMENT

PROTON ENERGY - $5.5 \pm .6$ MEV.

ALPHA ENERGY - $6.8 \pm .9$ MEV.

Figure 12

magnified. All the elements with the exception of Be were run more than once, and there was always agreement well within statistics for the different exposures of the same element except in the case of Au and U. The results given in Fig. 12 for Be, Al, Ni, and Ag show that the energy distributions of the protons and alphas change very definitely as a function of atomic number, indicating that the background effects are small for these cases.

The failure to measure the angular distribution of Au and U for these low-energy secondary particles should not cast doubt on the results obtained for Au and U using the apparatus which measured the momentum distribution at 0° . Here the results of different exposures for the same bombarding particles were reproducible, although the low-energy alpha yield fluctuated for reasons explained in Section VI-B. The angular distribution apparatus is known to have a higher background; only alpha bombardment of the targets is possible (as has been mentioned in Section II-B). The higher background in the angular distribution apparatus is due to several factors. The plates have less shielding around them; the median plane of the cyclotron is one inch or 50 percent closer to the top of the cart at the target position, and the plates are set higher in the cart and therefore are closer to the median plane.

C. Comparison with Other Experiments

Nuclear disintegrations produced in the heavy elements (Ag, Br) in nuclear emulsion have been studied extensively by several authors.^{7-18, 48, 49} Fig. 13 shows the energy spectrum of protons and alphas (actually hydrogen and helium isotopes) obtained for different nuclear excitation energies in the experiment of Harding et al.,⁷ in which nuclear emulsions were bombarded with cosmic ray particles. Fig. 14 shows the results obtained by Morinaga and Fry⁴⁹ from the capture of μ^- mesons in Ag and Br in the emulsion. In the latter case, the excitation energy is of the order of 30 to 40 Mev.

Figure 13

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Figure 14

The excitation energy for the different bombardments of Ag, Fig. 8, is estimated to be about 100 Mev. Comparing these results with Fig. 13(a) and Fig. 14, one sees that the shape of the proton spectrum is qualitatively the same. There appears to be a maximum in the region between 6 and 10 Mev for all these plots. As for the alpha spectrum, Fig. 13(d) and Fig. 14 indicate a maximum in the region around 15 Mev. Fig. 8 indicates that there may be a maximum in this region, although unfortunately this region is not explored by the apparatus used. Connecting the alpha points in Fig. 8 with straight lines is misleading, since there undoubtedly is a maximum in this region and at 20 Mev the yield should be decreasing rather than appearing to increase, as a straight line plot indicates.

The angular distribution of the black tracks (particles with less than 30 Mev) for the Ag and Br nuclei has generally been found to be isotropic, ^{7,12,19} although Bernardini, et al.¹⁷ found a forward peak. The results for Ag in Fig. 12 for 5.5 Mev protons appear to be isotropic. The rise at 135° can be explained by a small center-of-mass velocity: a proton being emitted at 135° in the laboratory system has a slightly higher energy (about one Mev) in the center-of-mass system than a proton emitted at 0° and 45° in the laboratory system. The proton yield is a very sharply increasing function of energy in this region, so a higher yield at 135° is to be expected. The fact that the alpha yield (6.8 Mev alphas), although very much lower than of protons, is also increasing with angle can likewise be explained by the increasing energy of emission in the center-of-mass system with increasing angle in the laboratory system.

It is not possible to interpret the chemistry experiments, in which the resultant nuclei are analyzed, so that a comparison can be made with the results found for this experiment. The chemistry experiments are quite fragmentary, since stable nuclei are not detected, and have been done thoroughly only for Cu. The results for 190 Mev deuteron bombardment of Cu indicate that reactions in which an alpha particle can

be ejected are more favored than reactions in which particles are ejected that are less tightly bound.⁵ For example, the yield of Mn^{52} is a hundred times greater than of Fe^{52} , although it requires the ejection of an extra proton rather than a neutron. Mn^{52} can be formed from Cu^{63} by the ejection of two alpha particles and three neutrons, while Fe^{52} has to be formed by emission of particles less tightly bound. The results of Batzel, et al.⁶ for the 340 Mev proton, 190 Mev deuteron, and 190 Mev and 380 Mev alpha bombardments of Cu indicate that yield for a given Z rises for nuclides nearest the region of stability, and that nuclides with the largest deficiencies or excesses of neutrons are found in the lowest yield. This result agrees with the studies of the spallation of arsenic.⁵⁰ The results for antimony⁵¹ indicate that the yields of neutron-deficient nuclei are larger than the yields of nuclei with neutron excess, indicating that charged-particle emission is forbidden by the coulomb barrier. As informative as these chemistry experiments may be, there is no direct way at present to connect them with the emission of charged secondary particles.

V. NUCLEAR MODELS PERTAINING TO THE LOW-ENERGY SPECTRUM OF SECONDARY PARTICLES

The black tracks of cosmic ray stars are generally associated with the low-energy spectrum of secondary particles. By definition, only particles emitted with energies less than 30 Mev are considered as belonging to this black-track group. There have been two models proposed to account for the low-energy spectrum: an evaporation model and a cascade model. In these models, a nucleus of approximately $A = 100$ is used for theoretical calculations, which represents a mean value for the heavy nuclei in emulsion (Ag and Br) for which statistical models would be expected to hold.

A. Evaporation Model

Considering the interaction of a fast nucleon with a nucleus as a two-step process, as was discussed in Section I, we assume that a definite amount of excitation energy has been transferred to the nucleus after the faster nucleons of energy above 30 Mev have left the nucleus. If this excitation energy is less than the total binding energy, the nucleus does not fly apart. Instead it behaves somewhat like a fluid in thermal equilibrium. The nucleons of which the nucleus is composed collide with one another much as do molecules in a gas or liquid. Again, in much the same way as in the evaporation of a molecule from a liquid, one of the nucleons may acquire by statistical fluctuation more energy than the average, and be able to leave the nucleus. This process goes on until the nucleus reaches a stable state. The disintegration from an excited state may then be treated as quite independent of the process by which it is formed.

The energy distribution of nuclear particles emitted from an excited nucleus has been derived by Weisskopf.²⁹ For large excitation energies, the probability of a neutron's being emitted with an energy between E and $(E + dE)$ is approximately of the Maxwellian form:

$$P(E) dE = \frac{E}{T^2} e^{-\frac{E}{T}} dE \quad (7)$$

where both the temperature T and energy E are measured in Mev and T is the temperature of the resultant nucleus. In the case of charged particles, equation (1) can be shown to be:

$$P(E) dE = \frac{E - V}{T^2} e^{-\frac{E - V}{T}} dE \text{ for } E > V \quad (8)$$

where V is the height of the potential barrier. Thus the effect of the barrier is simply to shift the whole energy distribution by an amount V .

The temperature is related to the excitation energy U according to $U = \beta T^n$, where β is a (dimensional) constant and n depends on the assumed interaction between nuclear particles (gas model, liquid drop, etc.). The Fermi gas model, in which the nucleons are assumed to be an assemblage of free particles (with kinetic energy very much greater than interaction energy) gives the relation:

$$U = KAT^2 \quad (9)$$

where A is the total number of nucleons and $K = \pi^2/4\epsilon$, ϵ being the kinetic energy of the highest occupied state in the unexcited nucleus, so that for $\epsilon = 22$ Mev, $K \sim 0.1$. The liquid-drop model assumes the interaction between nucleons to be similar to that between molecules in a liquid (interaction energy of the same order, or larger than, the kinetic energy). According to Bethe,²⁸ the excitation energy may be expressed in the following form:

$$\frac{U}{U'} = \tau^{7/3} + \tau^4. \quad (10)$$

The first right-hand term is related to surface waves, the second to volume waves. Here $\tau = T/T'$, where T' is the temperature at which the contributions of energy U' from volume and surface waves are equal.

The calculated T' for a Ag or Br nucleus is approximately 2 Mev. The calculated value for U' is 20 Mev. For high excitation energies, therefore, only volume waves need be considered, and $U = KAT^4$.⁷

Formulas (7) and (8) would be true for the energy distributions of molecules evaporating from a drop of water, but cannot be strictly applied to the multiple disintegrations of a nucleus, for the number of particles (~ 100) is so small that the nucleus cools appreciably after emission of each particle. Following the treatment of Bagge,³² using the Fermi gas model, one obtains for the average energy loss dU of the nucleus when dA neutrons are evaporated:

$$\begin{aligned}\frac{dU}{dA} &= 2KA \frac{dT}{dA} + KT^2 \\ &= 2T + E_0\end{aligned}\tag{11}$$

where from (7) $2T$ is the average kinetic energy of an evaporated neutron, E_0 is the binding energy per nucleon (assumed constant), and T is the instantaneous temperature. The process is treated as continuous and the emission of neutrons is assumed to be independent of that of protons. Integration of (11) gives the instantaneous temperature as a function of T_0 (initial temperature) and the initial and instantaneous mass numbers of the nucleus, A_0 and A , respectively. Integrating over a whole range of temperature, Bagge obtained the true energy distributions of the evaporated particles for any initial nucleus A_0 (Ag or Br). He found his spectrum could be expressed approximately by:

$$P(E) dE = \frac{E}{E + E_0} e^{-\frac{E}{T_0}} dE.\tag{12}$$

Equation (12) gives the spectrum for neutrons, and Bagge obtained that for protons by multiplying (12) by a factor corresponding to the mean Gamow factors for the initial and final nucleus.¹⁹

Harding, et al.⁷ carried out similar computations using both the Fermi gas model and the liquid-drop model. They found that the liquid-drop model gives an energy spectrum for protons which coincides with the gas model in the region from 0 to 15 Mev. Above 15 Mev, however, the energy spectrum drops rapidly and there is a large discrepancy between it and the experimental distribution. On the other hand, the Fermi gas model gives good agreement with experiment throughout the region where an evaporation model is expected to be valid. Figure 13 shows their experimental results, as amended by Perkins,¹¹ for the energy spectrum of protons and alphas for different nuclear excitation energies, and the calculated energy spectrum for the protons using a Fermi gas model.

It should be pointed out here that in the experimental identification of the black tracks of cosmic-ray stars it is possible to identify particles only as charge one or charge two by noting their specific ionization. The charge one tracks are classified as protons, although there is undoubtedly a considerable proportion of deuterons and tritons present, as the analysis of the grey tracks¹³ shows that the ratio of the number of deuterons and tritons to protons is about 0.3. The charge two tracks are supposedly alpha particles although here, too, there is contamination with He^3 and probably Li and Be nuclei. It should, therefore, be understood in discussing the experimental results for the analysis of cosmic-ray stars that "proton energy spectrum" really means the "hydrogen isotope energy spectrum," and the alpha energy spectrum includes He^3 and possibly neighboring nuclei of higher charge. However, the majority of the black tracks are undoubtedly protons and alpha particles, and the error in these experiments due to contamination by other isotopes is usually of the same order as, or smaller than, the statistical error.

The work of Bagge and Harding, Perkins and Lattimore was concerned only with calculating a rough fit to the experimentally determined proton energy spectrum. LeCouteur³³ has extended their work

in a comprehensive theory of nuclear evaporation. In his analysis LeCouteur has made several refinements. He has calculated more exact expressions for the energy lost to the nucleus per particle emitted. He has also obtained the probabilities at any instantaneous temperature for the emission of neutrons, H^1 , H^2 , H^3 , He^3 and He^4 , and the theory could also be extended to particles of higher charge. He allowed for cooling of the nucleus by integrating the probabilities for emission over the entire emission process. He has considered both the effects of the neutron excess in governing the control of the emission process and the effect of thermal expansion of the nucleus at high excitation energies.

From the experimental evidence of Harding, et al.,⁷ Fig. 13, there appears to be a considerable number of protons and alphas emitted below the Coulomb barrier. Harding, et al. assumed a potential barrier of 0.7, the barrier height for a nucleus of $A = 70$. The 0.7 takes into account barrier penetration. They explained the excess of low-energy protons by considering an additional barrier-penetration effect. LeCouteur and also Fujimoto and Yamaguchi⁴³ have suggested that in the latter stages of cooling the nucleus emits more neutrons than protons, increasing the ratio of atomic charge to atomic number. The nucleus then becomes more likely to lose positive charge, and the emission of decay protons is more probable than the emission of beta particles. This effect does not explain the emission of low-energy alphas. Experimentally it is found (Fig. 5) that the yield of low-energy alphas increases with excitation energy. LeCouteur found that the best fit with experimental data was obtained by assuming a potential barrier that decreases with increasing excitation energy, as was first suggested by Bagge.

LeCouteur integrated the equations of emission for various sets of parameters. The most important parameter is Λ , which is

related to nuclear level density. He used the following combinations:

$$\begin{aligned}
 &\text{a) } \mathcal{L} = 4 \quad V'_p = V'_d = V'_t = 5 \text{ Mev}, \quad V'_{\text{He}3} = V'_a = 10 \text{ Mev.} \\
 &\text{b) } \mathcal{L} = 5 \approx \sqrt{A/3.3} \quad \left\{ \begin{array}{l} V'_p = V'_d = V'_t = 1/2 V'_{\text{He}3} = 1/2 V'_a = 5(1 - U/2000) \text{ Mev.} \\ \text{c) } \mathcal{L} = 5.5 \approx \sqrt{A/2.7} \end{array} \right. \\
 &\text{d) } \mathcal{L} = \sqrt{A/3.3} \quad \left\{ \begin{array}{l} V'_p = 0.7V, \quad V'_d = 0.77V, \quad V'_t = 0.8V, \quad V'_{\text{He}3} = 1.6V \\ \text{e) } \mathcal{L} = \sqrt{A/2.9} \quad \left\{ \begin{array}{l} V'_a = 1.66V \text{ and } V = 6/1 + U/2000 \text{ Mev.} \end{array} \right. \end{array} \right.
 \end{aligned}$$

where V is the barrier height and V' is the effective barrier height after the penetration effect has been taken into account. The reduction of the potential barrier with greater excitation energy, assumed in b and c, is roughly that predicted by Bagge. The more drastic reduction in d and e seems to be required to explain the emission of slow alpha particles. The relationship between V and V' assumed in d and e is a fair approximation to the penetration formula of Bethe and Konopinski.⁴⁵

Figures 15 and 16 show results obtained using as parameters mean values of d and e. Figure 15 shows the total number N of tracks and the number n of protons, deuterons, tritons and alpha particles evaporated from a nucleus with initial excitation energy U . Figure 16 shows the energy spectrum for the hydrogen isotopes for five different values of the initial excitation energy.

Figures 17 and 18 show the theoretical and experimental results for the particles of charge one and charge two evaporated from the nucleus and forming stars which have an average of 10.2 prongs.

A quantity readily obtainable from observations on stars is the ratio of doubly to singly charged particles emitted. All the measurements give about the same order of magnitude, 0.4, which is found to change slowly with excitation energies, in good agreement with LeCouteur predictions. Also, for stars of about 10 prongs, LeCouteur gives a ratio of 0.3 for the proportion of deuterons and tritons in the singly charged particles, and this figure is in rough agreement with experiments attempting to differentiate the low-energy hydrogen isotopes.^{7,19}

Figure 15

Figure 16

Figure 17

Figure 18

It has also been pointed out by LeCouteur that in Weisskopf's formula there are no explicit factors representing the "probability of existence" of alpha particles inside the nucleus, and that if such factors were introduced one would no longer obtain agreement with experimental data. These "existence factors" only enter the formula through the dependence of the level density of the residual nucleus on the mass, binding energy, and charge of the emitted particle. The dependence is especially important at high energies and accounts for the broad maximum in the alpha-proton ratio.

B. Cascade Model

In analyzing the process of energy transfer one could also trace the history of each recoil separately, choosing the energy per collision by some random method. Goldberger³⁵ extended the ideas set forth by Serber¹ concerning the inelastic interaction of a high-energy nucleon with a heavy nucleus. The heavy nucleus was represented as a Fermi gas of nucleons. The incoming high-energy nucleon was considered to be well localized (its wavelength being much less than a nuclear diameter) and to interact with the nucleon gas by a series of nucleon-nucleon scatterings. The struck nucleon also interacted and, in this way, an internal nucleonic cascade was generated that proceeded until the moving nucleons either reached the edge of the nucleus and escaped or fell below the nuclear barrier and were thermally captured.

To treat complex cascades of this type, Goldberger employed the Monte Carlo method. The Monte Carlo method is a generally valid procedure for treating an ordered sequence of processes (A, B, C, ...) each of which is characterized by its own statistical distribution. One divides each statistical distribution into equally probable intervals, and then - starting with a random choice for A - chooses in sequence at random equally probable events for B, then for C, etc., until one finally arrives at the end state. It is obvious that for sufficiently fine intervals, what one does is merely to reproduce the process, and hence the inherent

statistical fluctuations in the final-state distribution curves should be the same for N Monte Carlo calculations as one obtains for results based on N experimentally observed events. Of course, this assumes that the statistical distribution curves put into the calculations are correct and describe completely what happens.³⁴

Goldberger's original evaluations were performed for the interaction of 90 Mev neutrons on a Pb nucleus. An experimental check of Goldberger's calculation by Hadley and York was interpreted to be at best only in partial qualitative agreement. The discrepancies may have been caused by the inapplicability of the model at these low energies, for which pick-up effects, multiple nucleon interactions, and refraction effects could be important.

Bernardini, Booth and Lindenbaum decided it was worth while to check this cascade model at higher energies of 300 to 400 Mev for neutrons and protons by a Monte Carlo calculation. The model would be intrinsically better at these energies since refraction effects, etc., here become less important. Besides, there is direct experimental evidence for a cascade model. From their experiment,¹⁷ bombarding electron-sensitive plates with 300 to 400 Mev neutrons and protons, they found that particles emitted with energies greater than 30 Mev are strongly collimated in the direction of the incident primary particle, which suggests a cascade mechanism. This result is in agreement with the fact that the grey tracks of cosmic-ray stars are composed primarily of protons and their angular distribution, also, is peaked in the forward direction. Bernardini, et al. also found that the angular distribution of the black tracks is not isotropic as an evaporation model would predict, but that 25 percent to 40 percent have a knock-on origin. This result has not been found in cosmic-ray work, where the angular distribution of protons and alphas with less than 30 Mev energy is found to be isotropic. This discrepancy is attributed to the energy difference of the primary particle; higher-energy primary particles may be expected to produce larger cascades, so that the low-energy protons tend to have an isotropic distribution.

Figure 19 shows the energy spectrum of the knock-on nucleons directly ejected. That fraction of emitted nucleons which consists of protons is assumed to be one-half. The results are based on 90 incident 400 Mev nucleons, of which 60 resulted in inelastic events and 30 went through the nucleus without interacting. The percentage of black tracks which are calculated to be knock-on protons is 30 percent. The remainder of the black tracks are attributed to the evaporation process. The calculated mean excitation energy for the evaporation process is 50 Mev.

This theory predicts only the number of neutrons and protons knocked out of the nucleus. Some production of deuterons, tritons, and the helium isotopes could be explained by a complicated pick-up process, but their number is supposedly relatively small. The emission of the large number of alphas observed, Fig. 13, is probably also ascribed to the evaporation process, although Bernardini, et al. do not mention this point. They take the viewpoint that the general tendency is to consider that the black tracks of cosmic-ray stars arise from an evaporation process following a very high internal excitation of the evaporating nucleus. They state that the results of their analysis imply that the residual nuclear excitation responsible for evaporation is quite low and that the essential process determining the characteristic of the stars is the internal nucleonic cascade generated. The evaporation contribution is only more or less a byproduct of the cascades.

C. Other Nuclear Models

Horning and Baumhoff⁴⁶ have worked out a theory of nuclear stars depending on a theory of nuclear transparency and on a theory of nuclear evaporation. The transparency was computed on the basis of a model proposed by Serber¹ and the evaporation was computed on the basis of the statistical model of the nucleus. Approximate values were calculated for the interaction between the nucleons and the incident particle, as well as for nuclear entropy and binding energies of the evaporated

Figure 15

particles. The results are in qualitative agreement with the experiment of Gardner and Peterson,¹⁵ in which nuclear emulsions were bombarded with 35, 90, 135, and 190 Mev deuterons. The theory is difficult to interpret. It combines stars produced in both the light and heavy elements in the emulsion.

Thus far the different models have only attempted to explain the emission of particles of $Z \leq 2$. For heavier particles, fragments, the evaporation model, or a fission hypothesis³⁷ can be used to explain the emission of low-energy fragments. However, there is no model or theory at present that can explain the emission of high-energy fragments (more than 4 Mev per fragment).

VI. DISCUSSION OF RESULTS

A. Angular Distribution

The most direct way of discerning the region of validity of the cascade and evaporation models is to measure the angular distribution of heavy nuclei for energies of the secondary particles varying from about 5 to 50 Mev. Because of the limitations of the size of the cart, the highest energy that could be measured for secondary protons and alphas in this experiment was approximately 6 Mev.

The results for Be and Al represented in Fig. 12 show a sharp falling off as a function of increasing angle. However, since alphas are the bombarding particles, the center-of-mass velocity is undoubtedly high enough -- even taking into account a considerable amount of incident momentum being carried off by fast ejected particles -- that there will be a considerable difference between the distribution actually occurring in the center-of-mass system and that measured in the laboratory system. There has been no lower limit set as to the number of nucleons necessary for a statistical theory, such as the evaporation model, to be valid. Since the compound-nucleus theory holds for the lightest elements, it would not be too surprising if Be could be explained by a two-step process. Nevertheless, to disentangle the results enough to determine the center-of-mass distribution for these light elements requires a considerable amount of supposition concerning the nature of the process giving rise to the secondary particles, and such an analysis has not been attempted.

The results for Ni and Ag are shown in Fig. 12. For these elements the center-of-mass velocity is small. For low-energy particles, however, it is significant, since in the region around 6 Mev the yield of protons is extremely energy-dependent (as one can see from the results for Ni and Ag in Figs. 7 and 8 and the prediction of Le Couteur for Ag shown in Fig. 16). In this energy region it appears that

the proton yield for Ni is a decreasing function of energy, while the proton yield for Ag is an increasing function of energy. Since the energy of emission in the center-of-mass system is larger with increasing laboratory angle for a constant laboratory energy, an isotropic emission in the center-of-mass system would show a peaking in the forward direction for Ni and a rise in the backward direction for Ag. This is what is observed in Fig. 12. The solid angle factor in going from the center-of-mass system to the laboratory system should also be taken into account, although it is quite small at low velocities. This factor tends to cause a peaking in the forward direction, and probably affects Ni more than Ag, since the center-of-mass velocity is probably less for Ag than for Ni. Qualitatively only, it appears that the proton angular distribution is isotropic for both Ni and Ag. The rise in the alpha yield with increased laboratory angle for both these elements can also be explained by similar arguments based on the fact that yield of alpha particles should be increasing with energy in the region. It is interesting to note that the alpha-proton ratio for particles of approximately 6 Mev emitted at 0° is the same for either 375 Mev or 240 Mev alpha bombardment, being 0.07 for Ni and 0.02 for Ag.

B. Energy Distribution of Protons and Alpha Particles Emitted at 0°

The element that can best be compared with theory is Ag, Fig. 8. The predicted proton distribution for the evaporation model as derived by LeCouteur is shown in Fig. 16. It can be seen that the shape of the curves is a very slowly varying function of excitation energy. The shapes of the experimentally determined spectra appear to be nearly similar for all bombardments. This fact is significant since, according to the evaporation model, the only effect of the bombarding particle should be in the total excitation energy given to the nucleus, and the resulting low-energy spectrum should be independent of the primary process. There appears to be a maximum in the region between 6 and 10 Mev, as predicted. It is estimated that the excitation energy for these bombardments is in the vicinity of 100 Mev. If one extrapolates LeCouteur's

curves to this excitation energy, then the ratio of 10 Mev protons to 20 Mev protons is about three to one. This also agrees very well with the experimental results. The proton distribution for the cascade model for proton bombardment is shown in Fig. 19 and it is estimated by Bernardini, et al. that the low-energy spectrum should be composed of 30 percent knock-out protons. An energy distribution composed of 70 percent evaporation protons and 30 percent knock-out protons would give a flatter distribution, with a ratio of the yield of 10 Mev protons to 20 Mev protons of about 2.5 to 1, which is a trifle low.

The predicted alpha particle distribution for Ag for excitation energies of the order of 100 Mev would have a similar shape, but the maximum would be shifted over to about 15 Mev. From the results shown in Fig. 8, not much can be said concerning the alpha spectrum, since the bulk of the alphas falls in the unexplored region between 10 and 20 Mev. However, as was previously mentioned, connecting the alpha points with straight lines is misleading since there is undoubtedly a maximum in this region and the yield should then be decreasing at 20 Mev rather than appearing to increase, as a straight line plot indicates.

The results for Be and Al are shown in Figs. 5 and 6. These distributions are complicated by the center-of-mass velocity. Here, as with angular distribution, no attempt has been made to unravel these distributions to get the true emission spectra. For Be, the yield of alphas is considerably higher than of protons at these energies, although it appears that the proton yield will be greater for larger energies.

The results for Ni, Au and U are shown in Figs. 7, 9, and 10. It can be seen that here, too, the shapes of the energy spectra of the same element for different bombardments are quite similar. The evaporation model would predict a maximum for protons at approximately 5 Mev for Ni and between 10 and 15 Mev for Au and U. The alpha peak would be expected to be approximately twice these values. The results obtained are consistent with these values. The rise in the alpha yield at 6 Mev for U is discussed in the next paragraph.

The alpha-proton ratio is shown in Fig. 12 for the three energies considered. The main effect for energies of approximately 6 and 10 Mev is to show the sharp falling off with increased atomic number, indicating the restriction in alpha emission as the coulomb barrier increases. The rise in the ratio for U is attributed to slow alpha emitters created during the bombardment. It should be pointed out that it takes a few minutes to remove the plates from the cyclotron after bombardments. In that time, alpha particles that are being emitted by slow alpha emitters are being collected in the plates. The lifetime for an alpha emitter emitting alphas of energies between 5 and 9 Mev would range from a fraction of a second to years. Thus the alpha yield found on the plates in the 6 Mev position depends on the speed with which the plates are removed from the cyclotron. The fluctuations of the alpha yield and in the alpha-proton ratio for the different bombardments is attributed to the different periods of time that the plates spent in the cyclotron after bombardment. For the 20 Mev position, the alpha-proton ratio is much higher for the heavy elements. In Au and U, there is a falling off of the ratio for the deuteron bombardment compared to the alpha and proton bombardments. The falling off is probably due to the fact that the very heavy nuclei retain a considerable amount of incident bombarding energy as excitation energy. Since the deuteron bombarding energy is about half that for the other two, the excitation energy is lower for this bombardment, which lowers the probability for alpha emission.

For Ag, LeCouteur has also calculated what the expected alpha-proton ratio should be. However, his values are for the integrated spectra of protons and alphas. Since only a small part of the differential spectrum has been obtained, it is not possible to integrate the spectrum to compare with the predicted value.

C. Other Secondary Particles

Tables II-IV and V-IX indicate that an appreciable number of other particles is emitted. The individual statistics are quite poor, however, and individual energies as shown in Table I vary considerably for

each plate, so that it is not possible to make direct comparisons as was done for the protons and alphas. In general, the yields of hydrogen and helium isotopes show the same coulomb-barrier effects as shown by alpha particles.

The results also indicate that secondary particles (fragments) of $A \leq 4$ are also emitted with high momenta. The yields seem to follow the curve for binding energy per nucleon, being high for the light and heavy elements and having a minimum at Ni. The yields of these fragments are much higher for the alpha and proton bombardments than for the deuteron bombardments, perhaps indicating that these yields are dependent on excitation energy.

Nothing has been said about neutron emission, since neutrons are not detected. However, it should be remembered that as the coulomb barrier increases, the probability of charged-particles emission decreases. The chemistry experiments on antimony reveal that neutron-deficient nuclei are formed in much greater abundance than neutron-excess nuclei, indicating that (primarily) neutrons are boiled off. The probability of charged-particle emission should be quite small at Au and U and, as a matter of fact, theorists consider only neutrons to be evaporated off in this region of the periodic table. Further chemistry experiments in this region should shed light on the relative probability of emission of charged particles or neutrons.

VII. GENERAL OBSERVATIONS

It is generally accepted at present that the two-step process best describes the high-energy interaction of nucleons with nuclei. However, there is some controversy concerning which step predominates, and the energy range of the secondary particles for which each step is valid. For a nucleus of mass 100, Bernardini, et al. believe that the knock-out process is the fundamental one and that for a 400 Mev primary nucleon only a small percentage (~10 percent) goes into the evaporation process. They have also extended the energy of the knocked-out nucleon down to the coulomb-barrier energy (~5 Mev). On the other hand, Harding, et al. and LeCouteur believe that the nucleus can be excited to excitation energies greater than the total nuclear binding energy, and secondary particles up to 30 Mev should be explained by the evaporation process. It would seem that both theories need some modification. The theory of Bernardini, et al. needs a higher low-energy cutoff for the secondary particles, and the evaporation-model enthusiasts should put a lower upper limit to nuclear excitation energy.

The experimental results obtained in this experiment appear to be consistent with the predictions of the evaporation model.

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TABLE CAPTIONS

Table I	Mean energies of secondary particles in Mev for the radius-of-curvature intervals considered. (These energies are uncorrected for energy loss in the target, although it is significant for particles of short range.)
Table II	Relative abundances of products emitted at 0° to the incident beam direction for 375 Mev alpha bombardment. Each element has been normalized to 100 percent for the number of particles found per unit solid angle per unit radius-of-curvature interval. The actual numbers of tracks found are in brackets and are listed below the percentages in each case.
Table III	Relative abundances of products emitted at 0° to the incident beam direction for 332 Mev proton bombardment. Each element has been normalized to 100 percent for the number of particles found per unit solid angle per unit radius of curvature interval. The actual numbers of tracks found are in brackets and are listed below the percentages in each case.
Table IV	Relative abundances of products emitted at 0° to the incident beam direction for 187 Mev deuteron bombardment. Each element has been normalized to 100 percent for the number of particles found per unit solid angle per unit radius of curvature interval. The actual numbers of tracks found are in brackets and are listed below the percentages in each case.
Table V	Alpha-proton ratio as a function of atomic number for the alpha-proton energies measured for each bombardment. (The errors shown are statistical errors expressed in standard deviations.)
Tables VI to IX	Relative abundances of products emitted at 0° , 45° and 135° to the incident beam direction for 240 Mev alpha bombardment. Each element has been normalized to 100 percent for the number of particles found per unit solid angle per unit radius-of-curvature interval. The actual number of tracks found is in brackets listed below the percentage in each case.

FIGURE CAPTIONS

- Fig. 1 Plan view of arrangement of apparatus to measure relative abundances of secondary particles emitted at 0° for three different radius-of-curvature intervals. The cart, loaded with copper shielding and with plates in the positions shown, enters the cyclotron vacuum tank through an air lock. The cart is low enough to be entirely underneath the circulating beam. The secondary particles spiral down slightly and enter the plates through the surface of the emulsion. Blocks of Wolfram are placed as roofs over the plates to reduce stray light and background tracks.
- Fig. 2 Plan view of arrangement of apparatus to measure relative abundances of secondary particles emitted at 0° , 45° and 135° for one radius-of-curvature interval. (Cart, shielding and geometry as in Fig. 1)
- Fig. 3 Schematic diagram of the trajectory of a secondary particle emerging from target and spiraling down and entering nuclear emulsion with plane projected angle β .
- Fig. 4 Representative sample of secondary particles resulting from 375 Mev alpha bombardment of Be. The solid lines are the calculated loci for most of the isotopes considered. The charge of each particle is determined to be one or greater than one by determination of the specific ionization. Particles whose ranges are displaced more than $7\frac{1}{2}$ percent of the calculated range are regarded background.
- Figs. 5 Relative yields of secondary protons and alpha particles to 10 emitted at 0° to incident beam direction for each bombardment, plotted as a function of energy. The numbers of tracks found per unit solid angle per unit energy interval are in arbitrary units. (The errors shown for the number of particles found are statistical errors expressed in standard deviations.) The energy resolution shown for each point is the entire interval considered and is found by combining the energy spread determined by scanning a finite amount of track and the loss of energy by ionization caused by the finite thickness of the target.

- Fig. 11 The alpha-proton ratio as a function of atomic number. (The results in Table 5, shown graphically.)
- Fig. 12 Relative yields for the angular distribution of secondary protons and alphas resulting from 240 Mev alpha bombardment of Be, Al, Ni and Ag. The number of tracks found per unit solid angle per unit energy interval is in arbitrary units.
- Fig. 13 Energy distributions of protons (a, b, c) and alpha particles (d, e, f) emitted from stars of different prong number in silver and bromine nuclei, C-2 emulsion.
(a) and (d) stars of 3-6 (excitation energy $U \sim 170$ Mev)
(b) 10-14 prongs ($U \sim 550$ Mev)
(c) 15-22 prongs ($U \sim 700$ Mev)
(e) 7-16 prongs ($U \sim 500$ Mev)
(f) 17-31 prongs ($U \sim 830$ Mev)
- Fig. 14 The energy distribution of protons and alpha particles from one-prong stars in silver and bromine in emulsion resulting from μ^- capture. The excitation energy is believed to be approximately 30 to 40 Mev. (Morinaga and Fry⁴⁹)
- Fig. 15 The total number N of tracks with numbers n of protons, deuterons, tritons and alpha particles evaporated from a nucleus with initial excitation energy U . Parameters used to compute these curves are mean values of (d) and (e). The parameters are given in Section V-A. (Le Couteur³³)
- Fig. 16 The energy spectrum of the evaporated particles of charge e for five different values of the initial excitation energy. Parameters used to compute these curves are the mean values of (d) and (e). The parameters are given in Section V-A. (Le Couteur³³)
- Fig. 17 Theoretical and experimental results for the energy spectrum of particles of charge e evaporated from stars of 10.2 prongs. The four theoretical curves b, c, d and e are for different sets of parameters given in Section V-A. (Le Couteur³³)

- Fig. 18 Theoretical and experimental results for the energy spectrum of evaporated particles of charge $2e$ from stars with an average of 10.2 prongs. The four theoretical curves b, c, d and e are for four different sets of parameters. The parameters are given in Section V-A. (Le Couteur³³)
- Fig. 19 Energy spectrum of nucleons knocked out of the nucleus. The fraction of nucleons which is protons is assumed to be one-half. These results are based on a Monte Carlo calculation for 90 incident 400 Mev nucleons, of which 60 resulted in inelastic collision and 30 went through the nucleus without interacting. (Bernardini, Booth and Lindenbaum³⁴)