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Interactions of energetic gold nuclei in nuclear emulsions

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The nuclear interactions of ${}^{197}_{79}$Au nuclei of initial energy 990 MeV/nucleon have been studied in nuclear emulsions as they slow down and stop. Typically, these interactions are fragmentations of the incident nucleus into an average of 2.0±0.3 fragments with $Z \geq 3$ and 4.2±0.2 helium nuclei. As many as eight $Z \geq 3$ fragments or 22 helium nuclei have been observed to be produced in a single interaction. The dependence on incident energy and target nucleus is discussed. Some 7% of the interactions appear to be fission in flight of the excited projectile nucleus emerging from the interaction, with the release of two highly charged fragments that contain most, if not all, of the incident charge. The charge distribution of these fragments ranges from symmetric to highly asymmetric.

I. INTRODUCTION

Gold nuclei, ${}^{197}_{79}$Au, accelerated at the Lawrence Berkeley Laboratory (LBL) Bevalac to an incident energy of 991±3 MeV/nucleon, have been observed undergoing nuclear interactions as they slow down and stop in nuclear emulsion. Two stacks, each made up of 24 Ilford G5 600 μm pellicles 15.2×5.1 cm in size, were exposed with the particles incident on the 5.1 cm side. One of the stacks was also exposed to a beam of 1.7 GeV/nucleon ${}^{55}_{25}$Mn nuclei, which were used for the normalization of some charge measurements. The stacks were oriented so that the emulsions were parallel to the beam, and most of the incident nuclei remained in one pellicle until they interacted or were brought to rest by ionization energy losses. The stopping of these Au nuclei and the non-Z^2 terms required to explain the energy losses observed have been discussed elsewhere.[1] In this paper we are concerned with the nuclear interactions produced by these very heavy projectile nuclei as they slow down and come to rest, while traversing the composite medium of the nuclear emulsion, which is composed of 26% AgBr, 34% CNO, and 40% H, by number.

The characteristics of these interactions can be directly compared with those produced in nuclear emulsions by lighter nuclei[2] as well as with recent reports of the interactions produced by ${}_{92}$U nuclei.[3,4] They can also be compared, less directly, with the results obtained by bombarding gold foils with energetic heavy ion beams.[5–7] In this paper we report our phenomenological results on a sample of interactions as a function of energy and of target type. Although these results are statistically limited, they do show that there is a significant fission yield, with both symmetric and asymmetric products, and a wide range of fragmentation modes which depend on the nature of the target nucleus and on the incident energy.

II. MEAN FREE PATH AND CROSS SECTIONS

The track of each incident nucleus was found by scanning 1 mm below the top edge of the pellicles and was then traced back to the top and down into the emulsions until the nuclei either interacted or came to rest. Each interaction detected was analyzed and any heavy ($Z \geq 26$) fragments produced were traced further until they either interacted, came to rest, or left the stack.

The overall mean free path, λ_{Au}, found for the Au nuclei is 5.60±0.26 cm of emulsion corresponding to a cross section of $\sigma_T = 2280 \pm 106$ mb. Figure 1 shows the values of λ in each 100 MeV/nucleon interval and is consistent with there being no significant energy dependence, although a slow decrease with increasing energy cannot be excluded. This value of λ_{Au} can be compared with that of 4.00 cm ($\sigma_T = 3185$ mb) predicted from the known composition of nuclear emulsions and an extrapolation of the relationship found for charge-changing cross sections measured for lighter ($Z \leq 26$) projectiles by Westfall *et al.*[8] The large discrepancy is at least partly consistent

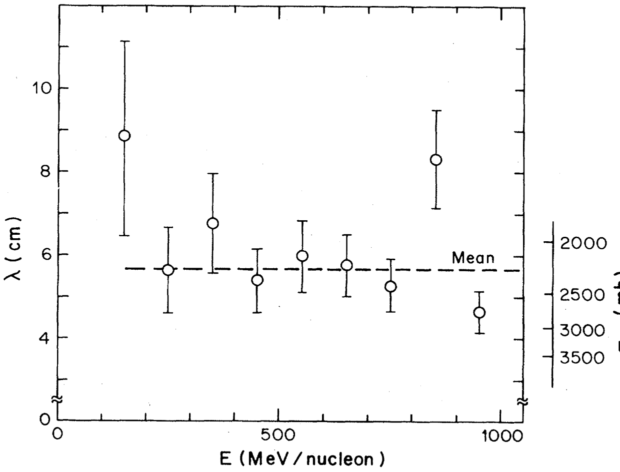

FIG. 1. Mean free paths of Au nuclei in nuclear emulsion in cm as a function of energy in MeV/nucleon. Also shown is the equivalent cross section, σ, in mb, calculated from $\lambda = A/(6.02 \times 10^{-4} \sigma\rho)$, where $A = 29.3$ and $\rho = 3.815$ g/cm^3. Errors shown are statistical, based on $\sqrt{n}$.

with the observation by Brewster *et al.*[9] that Au nuclei in targets of C and CH_2 have cross sections that are some 20% less than those predicted.[8] Our observed λ_{Au} can also be compared with that reported[3,4] for $_{92}U$ nuclei of similar energy of 3.78 ± 0.15 cm and 3.67 ± 0.12 cm.

Even if we adjust these λ_U by an $A^{2/3}$ factor of 1.13, we cannot bring them into accord with our λ_{Au}. However, it is reported that some 50% of all the observed $_{92}U$ interactions are due to fissionlike events, whereas only some 7% of the Au interactions have such characteristics (see Sec. IV). Hence, it may not be appropriate to compare the measured mean free paths of these two nuclear species, since a different interaction channel dominates the U nuclei. It may be noted that the mean free path for nonfissionlike interactions reported for U is 7.44 ± 0.35 cm,[4] compared to the 6.00 ± 0.28 cm that we found for Au.

Apparently, when U nuclei make interactions with large impact parameters they characteristically undergo fission, instead of suffering a small charge change, thus producing a readily detectable interaction, rather than one that could be missed during the scanning. The very thick primary tracks of these high Z nuclei in nuclear emulsion suggest that it would be difficult to detect small interactions in which only a few, visually insignificant, particles are released from *both* the projectile and target nuclei. Specifically, if N_h (the number of black or grey prongs from the target) is small and only one or two fast protons are relased from the projectile, then the interaction will be almost undetectable. Whether many such interactions do indeed occur cannot be reliably determined by rescanning if their detection probabilities are too small; however, we can compare the population of interactions detected produced by these Au nuclei with a population of interactions produced by lighter projectile nuclei, where the detection problems should be reduced. In Fig. 2, the N_h distribution observed in this work is compared with that obtained[2] for incident cosmic ray nuclei in the charge range $20\leq Z\leq 28$. In both data sets the percentage of events with $N_h\leq 1$ is $22\pm2\%$. These comparisons show that the Au interactions do not exhibit any significant lack of interactions with small N_h. This seems to imply that the majority of interactions with small N_h show enough breakup of the projectile to be readily detectable and vice versa. Nevertheless, in what follows it should be kept in mind that it is possible that the sample of interactions discussed here could be biased, lacking examples with small N_h and small ΔZ (with no fast He or light fragments). In general, the effects of such a bias would not materially alter our conclusions.

III. INTERACTION TYPES

Two principal classes of interactions are observed. The great majority, 435 of 465, resemble interactions produced by lighter projectile nuclei with fragmentation of the projectile and the release of nucleons and helium nuclei. In addition, 30 interactions were observed for which all, or nearly all, of the charge of the projectile was conserved in the form of two heavy fragments, resulting in an apparent bifurcation of the nucleus. These events are interpreted as a fission of the projectile in Sec. IV where it is shown that the kinematics are consistent with such a claim.

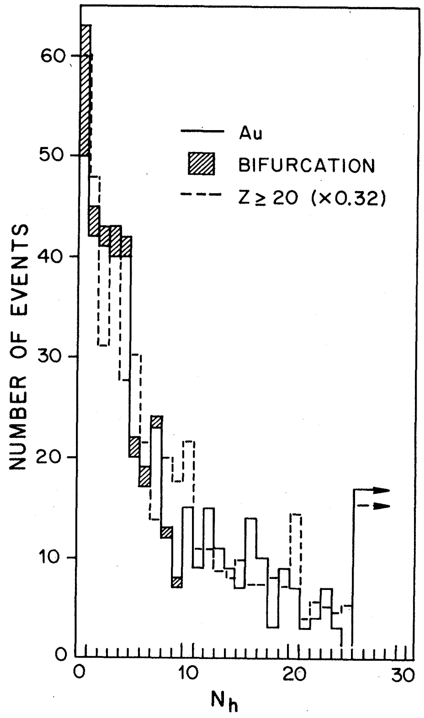

FIG. 2. Distribution in N_h for the Au initiated interactions observed. Bifurcation events with $\Delta Z\leq 5$ are shown shaded. For comparison, the N_h distribution for interactions initiated by cosmic ray nuclei (Ref. 9) with $Z\geq 20$ is shown as a dashed line, normalized by a factor of 0.32.

A. Interactions with fragmentation

Gold nuclei at these energies are essentially never broken up into just nucleons and helium nuclei, even in collisions with Ag or Br targets. Out of the 465 interactions studied in a systematic manner in this sample, only six have no fragment with $Z\geq 3$ emerging from the projectile nucleus, while 50% produce two or more such fragments. The degree of breakup is displayed in Fig. 3, which plots the charge of the heaviest fragment, Z_{TOP}, as a function of the sum of the charges of all the other fragments with $Z\geq 3$.

The number of fragments other than Z_{TOP} is shown in the figure and can be as great as seven. Points lying to the right of the upwardly inclined line must have had multiple light fragments, while charge conservation bounds the plot from above. Those interactions that we describe as bifurcation events are also shown.

Excluding the bifurcation events we can separate the remaining interactions into two main classes based on the observable degree of breakup of the target nucleus as revealed by the number of slow particles emitted. The distribution in this number, Fig. 2, shows a clear break at $N_h=8$, distinguishing interactions with the heavier target

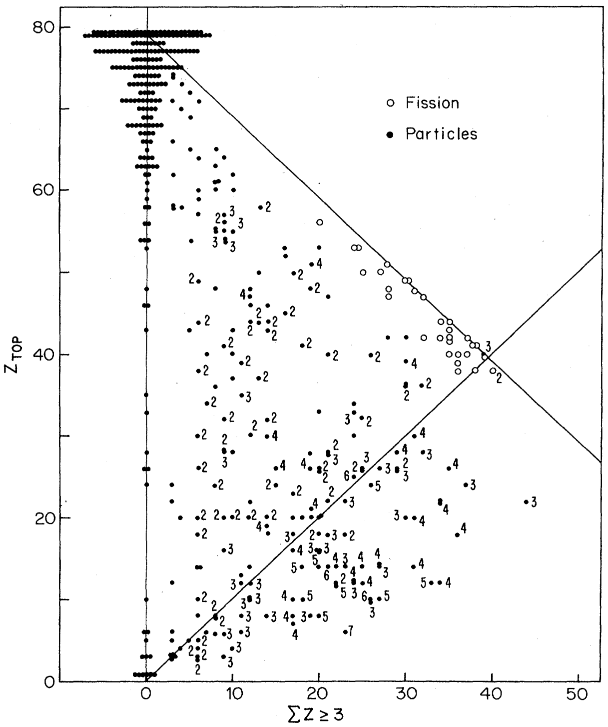

FIG. 3. Cross plot of the charge of the heaviest fragment, Z_{TOP}, against the sum of all other fragments with $Z \geq 3$ produced in the interaction. The number of these other fragments is shown whenever there was more than one such fragment.

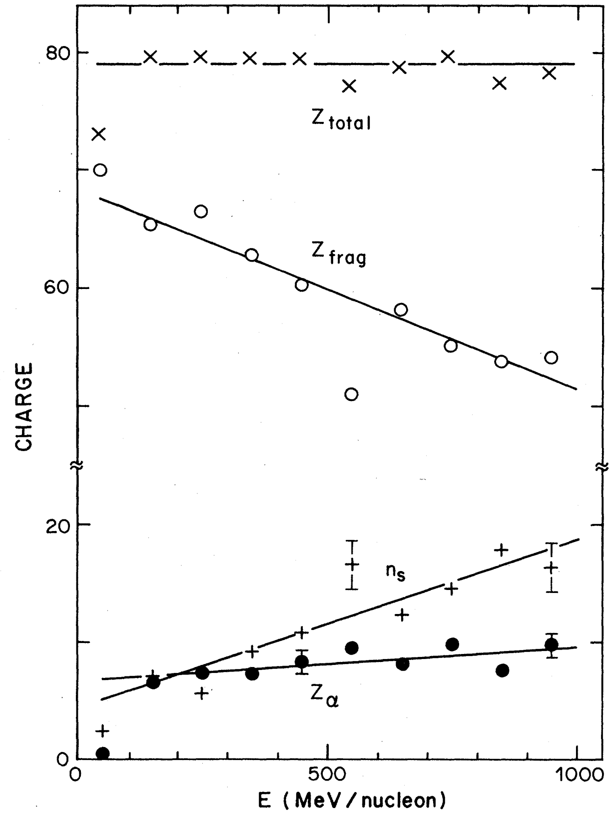

FIG. 4. Plot of the charge released as a function of energy. Curves are shown for singly charged particles, n_s; helium nuclei, Z_α; and for the sum of all fragments with $Z \geq 3$, Z_{frag}. Typical statistical errors are shown on a few points.

nuclei, Ag or Br, with relatively small impact parameters from those with either the lighter target nuclei or with large impact parameters. Of the 435 interactions included in this sample, 273 had $N_h \leq 7$, which from the relative cross sections implies that only some 13% of these were actually peripheral interactions with heavy Ag or Br nuclei.[10]

The characteristics of the interactions have been studied based on the above N_h separations into "light" and "heavy" targets and on the known incident energy of each projectile nucleus. Apart from the lowest energy interval, 0–100 MeV/nucleon, where $\langle N_h \rangle = 3.5 \pm 0.9$, $\langle N_h \rangle$ is essentially constant with energy at 7.6 ± 0.8, showing that the separation into light and heavy targets is not energy dependent, which is consistent with the near energy independence of the interaction mean free paths.

The energy dependencies of the number of singly charged particles emitted, n_s, of the charge carried on helium nuclei, Z_α, and of the total charge emitted on heavy $(Z \geq 3)$ fragments, Z_{frag}, are shown in Fig. 4. It can be seen that Z_α is weakly energy dependent, increasing from 3.5 to 5.0 alphas/interactions from 150–950 MeV/nucleon. n_s shows a considerable linear increase which presumably represents mostly an increasing degree of breakup but also modest meson production at the higher energies. That the contribution of meson production is indeed modest is indicated by the near constancy of Z_{total} $(=Z_{\text{frag}}+Z_\alpha+n_s)$ over the entire energy range. This is consistent with the observations of, for example, energetic ^{40}Ar nuclei on KCl targets,[11] which show that $\langle n_\pi \rangle$ is less than ≈ 3 at 1 GeV/nucleon even for "central collisions" which are only some 10% of all interactions. The dependencies of n_s and n_α on N_h class are shown in Figs. 5 and 6 and clearly show that heavy targets generally result in the release of more singly charged particles and helium nuclei than do light targets.

The considerable energy dependence of n_s shown in Fig. 4 must mostly be a consequence of the increasing degree of breakup as the available energy increases. This is reflected by the decreasing Z_{frag} with energy, which is most marked for $N_h > 7$ events, as one might expect. It should be noted that although Z_{frag} decreases, the number of individual fragments with $Z \geq 3$ is essentially independent of energy at 2.02 ± 0.27 fragments per interaction. If the nucleons in fragments are regarded as spectator nucleons, then this implies that as the energy increases, the fraction of spectator nucleons decreases. It also implies that at energy < 1 GeV/nucleon the fragmentation parameters are energy dependent.

The yields, in percent, of fragments produced on light and heavy targets, are shown in Fig. 7. It can be seen that for light targets there is a high yield of heavy fragments,

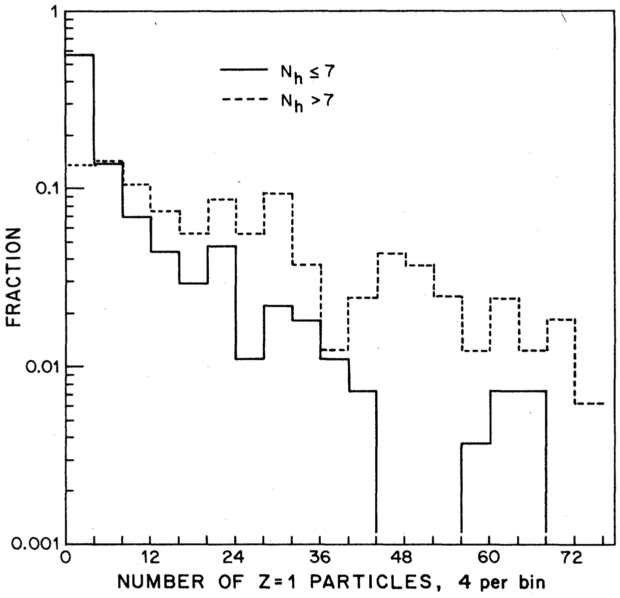

FIG. 5. The fraction of interactions that release a given number of singly charged particles for interactions with light, $N_h \leq 7$ and heavy, $N_h > 7$ targets. Each number bin is four units wide.

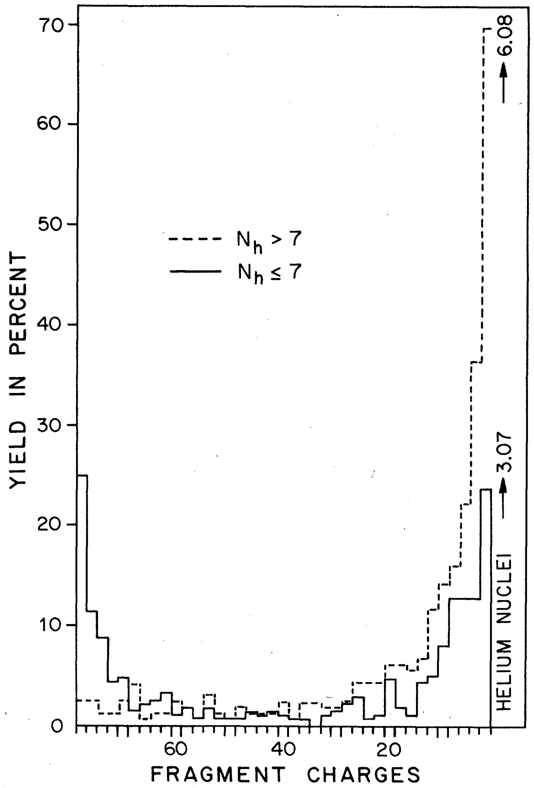

FIG. 7. The percentage yield of fragments of different charges for $N_h \leq 7$ and $N_h > 7$. Each charge bin is two charge units wide apart from that for $Z = 3$. The mean number of helium nuclei per event is given in each case.

with charge changes, $\Delta Z \leq 6$, then a low, but constant, yield for intermediate ΔZ, followed by an increasing yield for large ΔZ, those with $Z \leq 16$. On heavy targets, however, there is no significant peak in the yield for small ΔZ, but a much larger increase for the light fragments, $Z \leq 20$, once again illustrating the greater degree of breakup caused by heavy targets. Since some 19% of the interactions with heavy targets are included in the $N_h \leq 7$ class and since these must be peripheral and thus are most likely to have a high yield of heavy fragments, the striking difference in yield for small ΔZ may not be as significant as it appears. However, the difference at large ΔZ is clearly significant and not an artifact of the N_h selection.

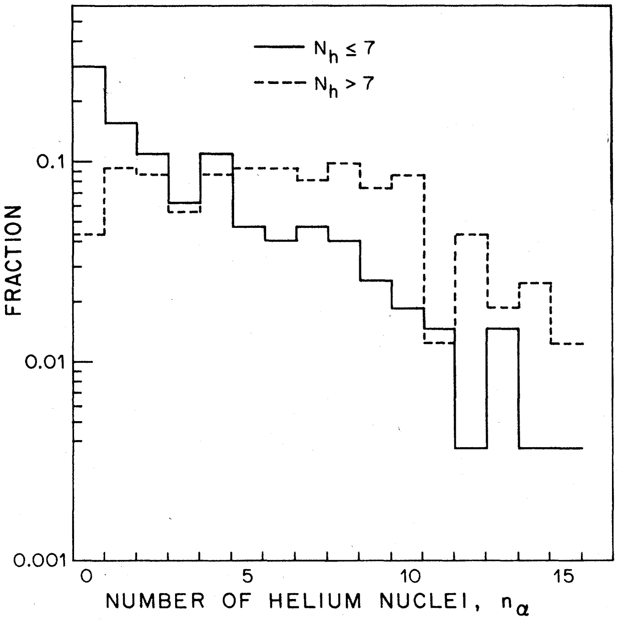

FIG. 6. Similar to Fig. 5 for helium nuclei. Each number bin is only one unit wide.

In addition to examining the fragments of the projectile nucleus, we have also studied the angular distribution of the slow particles emitted from the target nucleus. These particles are the N_h that characterizes each interaction and consist of all particles with energy losses that are greater than $1.4 I_{\min}$ ($E \leq 400$ MeV for protons) and are not associated with the projectile. By selecting interactions with $N_h > 7$, we ensure that we are considering heavy target nuclei, and by considering only very slow particles, those with ionization greater than that of $\simeq 30$ MeV protons, we eliminate any confusion with projectile fragments. These slow particles are presumed to be evaporated isotropically from the excited residual target nucleus in its own frame of reference. A deviation from isotropy in the laboratory system should correspond to a measure of the momentum transferred from the projectile to the target.

The ratio of forward to backward black tracks (F/B) has been measured[12] for interactions with $N_h > 6$ produced by 4.5 GeV/c protons to be 1.3 ± 0.1. If we assume the mean black track is produced by a 200 MeV/c (~ 20 MeV) proton, then $F/B = 1.3$ corresponds to a longitudinal momentum of the target nucleus of ~ 25 MeV/c per nucleon. For comparison,[13] cosmic ray nuclei with $6 \leq Z \leq 26$ and energies > 1.5 GeV/nucleon produce interactions with $N_h > 7$ that have $F/B = 1.42 \pm 0.03$, only marginally higher than for the proton interactions. Our gold interactions show a much larger effect, with $F/B = 2.44 \pm 0.10$ for $N_h > 7$ corresponding to $p_{\parallel} \simeq 85$ MeV/c per nucleon. This ratio is essentially independent of N_h, with $F/B = 2.40 \pm 0.20$ for $N_h \geq 20$. Clearly, in reasonably central collisions between massive and relatively low energy projectiles and heavy targets, appreciably more momentum is transferred to the target nucleus than by lighter and more energetic projectiles. Any kinematic analysis of longitudinal momenta of the projectile fragments should take this into account. However, the momentum transfer could be much smaller for peripheral collisions and an assumption of longitudinal momentum constancy for the projectile might be justifiable, but needs to be verified. It cannot be *a priori* assumed in an analysis of the bifurcation events.[4]

B. Discussion

The characteristics of the interactions described here show that it is extremely difficult to completely disrupt a heavy nucleus into its individual nucleons even when it is bombarded by energetic heavy nuclei such as silver or bromine (reversing the frame of reference). Instead, a residual, "spectator" nucleus is generally left in an excited state after the initial collision and then decays by an evaporation process, similar to that observed when target nuclei are excited by energetic projectiles. The surprising result observed here is the large multiplicity of fragments of appreciable charge, $Z \geq 3$. These fragments have appreciably less transverse momentum than the accompanying helium fragments, which is entirely consistent with evaporation. They are commonly not detected from target evaporation due to their low emissions energies, and in the case of relatively light projectile nuclei are not so copiously produced.

IV. BIFURCATION EVENTS

Some 7% of all the observed interactions show fission-like characteristics, with most or all of the incident charge in the projectile remaining in just two ongoing fragments. These events occur at all energies and the fragments may have a wide range of charges. Apart from the unusual frame of reference in this study, we would expect these events to resemble those observed when gold foils are bombarded by beams of high energy protons or light nuclei. Such studies have been reported using protons of 190 MeV,[14] 1 GeV,[15] and heavy ions, ^{20}Ne at 0.25–2.1 GeV/nucleon.[5–7] In each case, the masses of the fragments emerging from the foil and produced in correlation have been measured by solid state detectors. The cross sections observed for fission of gold by energetic protons was 71 ± 7 mb for 1 GeV protons,[15] and less at the lower energies.[14] The masses of the fragments have generally been consistent with symmetric fission, i.e., with an asymmetry ratio, $S = |(Z_1 - Z_2)/Z_T|$, close to zero, although the distributions in S are not quoted.

The events shown in Fig. 8 have been analyzed as bifurcation events in order to see whether they are kinematically consistent with fission of the incident Au nuclei. In this analysis we have used the range-energy relation[1] established for these nuclei to determine the incident momentum of the primary nucleus, p_0, and have measured the emission angles, θ_1 and θ_2, of both fragments relative to the incident particles. The charges of the fragments have been estimated from measurements on the taper tracks of those that come to rest before interacting, or from the characteristics of the secondary interactions produced. Examination of these estimates and comparison with the requirements of charge conservation suggest that, in general, these estimates have an accuracy of ±2 to 3 charge units. Measurement of the emission angles allows us to estimate the transverse momenta of each fragment, $p_{\perp}$, but the experimental uncertainties preclude any meaningful analysis of the longitudinal momenta.

Each event is analyzed in terms of the following model. It is assumed that the incident nucleus makes a peripheral interaction with a target nucleus which leaves the great majority of the incident nucleus unfragmented although highly excited. In this interaction this "residual" nucleus receives an impulse that imparts a total momentum of P_i to it. The residual nucleus then bifurcates, imparting equal and opposite transverse momenta of $A_1 p_1$ and $A_2 p_2$

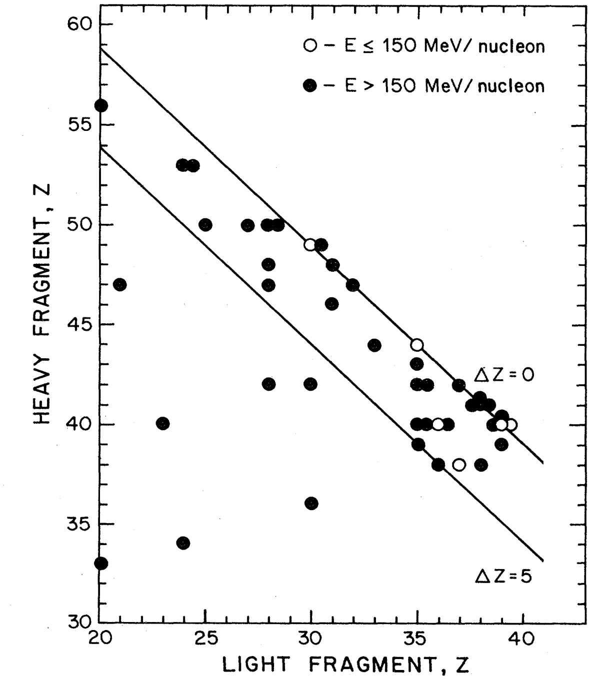

FIG. 8. Cross plot of charge on the heavy fragment versus that on the light fragment for bifurcation events. Those with $E_0 \leq 150$ MeV/nucleon are shown separately. Also shown are lines for $\Delta Z = 0$ and 5.

to the two fragments of Z_1 and Z_2 charge. If this model is to be interpreted as the fission of the residual nucleus, then P_i would be expected to be relatively small and the values of $p_{\perp 1}$ and $p_{\perp 2}$ should imply energy releases that do not significantly exceed the fission energy release of ~ 0.8 MeV per nucleon, and on average should be $\sqrt{2}$ less, due to the inclusion of the longitudinal momenta components.

In order to calculate specific values for these momenta, it is necessary to make the further assumption that both fragments have the same neutron to proton ratio ($A_1/Z_1 = A_2/Z_2$), and that this ratio is the same as that in the incident nucleus ($A_1/Z_1 = A_T/Z_T$). If instead it is assumed that n neutrons are emitted separately, so that this latter assumption is not valid, then a correction factor can be applied that depends on the characteristics of the individual events but is relatively minor. For example, with $n = 10$ and the worst case of a highly asymmetric pair of fragments, the corrections to $p_\perp$ are 1.075 and 0.962 for the light and heavy fragments, respectively. The energies per nucleon for each fragment implied from these momenta are corrected by the square of these factors but the mean energy released as transverse momentum, given by

$$E_\perp = \frac{Z_1 E_1 + Z_2 E_2}{Z_1 + Z_2} = \frac{p_0^2}{2m} \frac{Z_1 Z_2}{Z_T^2} (\theta_1 + \theta_2)^2 ,$$

is essentially unchanged.

Experimentally, although the emission angles in the plane of the emulsion can be measured with a precision that is typically of the order of ±1%, those perpendicular to the emulsion plane can only be measured to some ±5%. The accuracy with which $(\theta_1 + \theta_2)$ can be determined is thus geometrically dependent and varies appreciably from event to event. In addition, the displacements of the fragments from a plane that includes the projectile, the quantity that determines the transverse component of P_i, are too small to be reliably determined. The nominal values of E_i, the energies per nucleon implied by the calculated values of P_i, are typically less than 0.2 MeV/nucleon (mean of 0.17 MeV/nucleon). Consequently, the effects of P_i have been neglected in the analysis and $(\theta_1 + \theta_2)$ calculated directly from the measured separations between the fragments. This neglect of P_i is consistent with the observation by Kaufman *et al.*[7] that for Ne on Au producing fissionlike events, $P_i \lesssim 200$ MeV/c for small ΔA ($E_i \lesssim 0.11$ MeV/nucleon).

This analysis has been confined to events with a primary energy $E_0 > 150$ MeV/nucleon, in order to reduce the uncertainties in p_0. In a systematic scan for all interactions, 24 events were found that showed a charge release of $\Delta Z \leq 5$ and could be analyzed as examples of bifurcation. A further seven events were found in a similar scan, but one in which the other interactions observed were not analyzed in detail. In addition, there were six low energy, < 150 MeV/nucleon events and seven with $\Delta Z > 5$.

The 31 examples of bifurcation with $\Delta Z \leq 5$ showed values of E independent of E_0, Fig. 9, with an overall mean $\langle E_\perp \rangle$ of 0.55 ± 0.27 MeV/nucleon. Figure 10 shows $E_\perp$ as a function of the asymmetry ratio, S, and indicates that $E_\perp$ is not a strong function of S. In fact, for $S < 0.15$, $\langle E_\perp \rangle = 0.51 \pm 0.30$ MeV/nucleon, while for $S > 0.15$, $\langle E_\perp \rangle = 0.60 \pm 0.22$ MeV/nucleon. Within the limited statistics there is no evidence that the kinematics of the symmetric events differ from those with large asymmetries, although those events with $\Delta Z > 5$ had a significantly larger $\langle E_\perp \rangle = 1.04$ MeV/nucleon. Furthermore, the energies released are not significantly larger than the Q values for symmetric or asymmetric fission of some 0.80 or 0.66 MeV/nucleon, respectively. We conclude that we are observing examples of the fission in flight of the incident gold nuclei.

Fission of gold nuclei induced in this manner can be

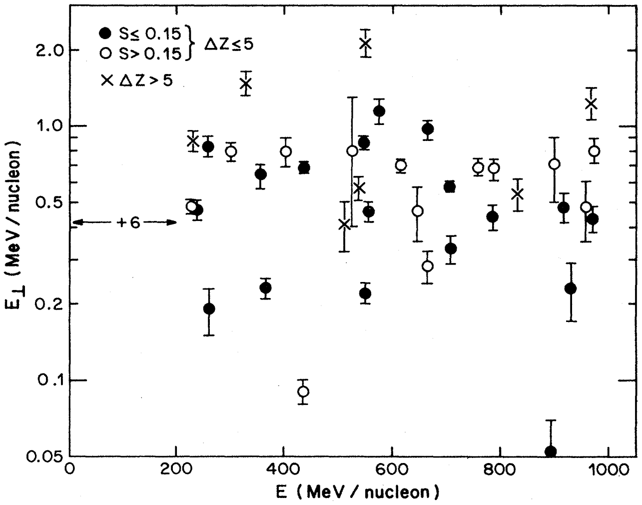

FIG. 9. Deduced energy from perpendicular momenta measurements, $E_\perp$ as a function of energy at interactions E_0. Events with symmetry ratios $S \leq 0.15$ are shown separately from those with greater asymmetry. Events with $\Delta Z > 5$ are shown as crosses. Errors are shown on all points.

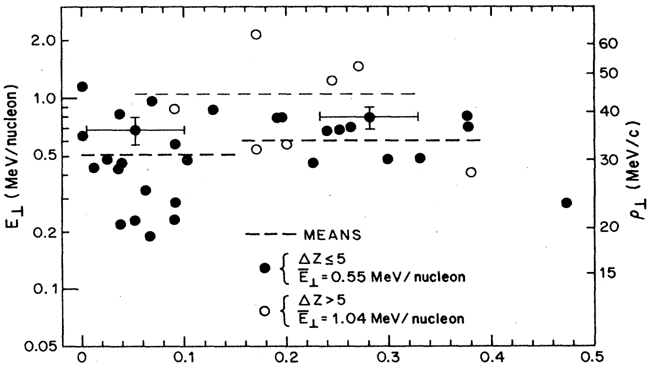

FIG. 10. $E_\perp$ shown as a function of asymmetry ratio S. Also shown are the mean values of $E_\perp$ for two classes of S values and for events with $\Delta Z > 5$.

compared with earlier observations of fission induced in light nuclides by bombardment with energetic particles. Plasil *et al.*[16] bombarded ${}^{209}_{83}\mathrm{Bi}^{126}$ with 36 MeV protons and observed a spread in A (or Z) that was considerably narrower than that seen here, Fig. 11. The events observed here with the largest values of S would have an extremely small probability of being observed if the true distribution were that of Plasil *et al.* However, Au has neither a magic number of neutrons, 126, nor of protons, 82, and hence might be expected to show different fission behavior. In fact, it appears that, contrary to prediction, highly asymmetric fission is more favored for the Au nuclei than it is for the heavier Bi nuclei.

Fission of gold foils bombarded by ^{20}Ne of up to 2.1 GeV/nucleon has been observed by Warwick *et al.*,[5–7] who separated events in which at least one intermediate mass fragment was observed to be emitted into two classes. One class, distinguished by high c.m. energy, low "multiplicity," and association with a second intermediate mass fragment, is identified as fission; the other class, with low c.m. energy and high multiplicity, is identified with a process called "deep spallation." In general, it is difficult to compare these results with those presented here due to the different frames of reference and the inherent biases of the triggers used in the gold foil experiments. While our results include every charged particle from the projectile being observed, those of Warwick *et al.*[5–7] depend upon a trigger of a heavy particle with $E > E_{\mathrm{min}}$ being emitted at ~90° in the laboratory, but have much greater statistical weight. However, the general features deduced by Warwick *et al.* are confirmed. There is a significant fission yield and there are events that correspond to the deep spallation process. In addition, there is a rich and complex yield of other $Z \geq 2$ fragments that could not be resolved by these authors, but which should be explained by any theoretical models of the interaction process.

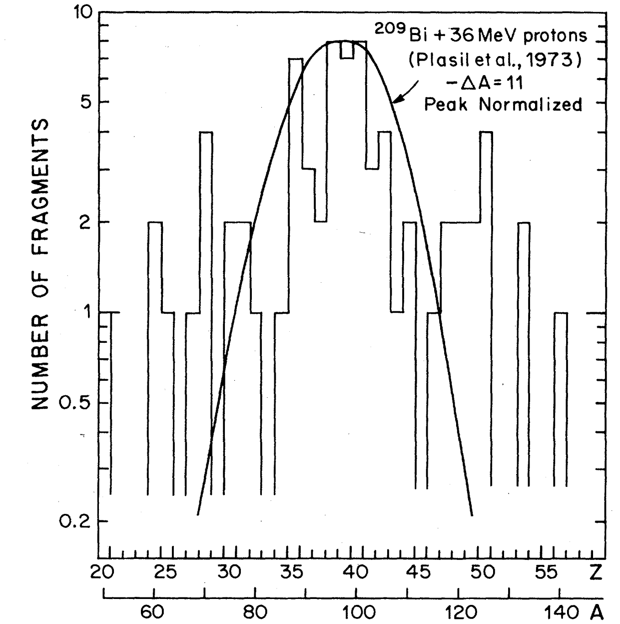

FIG. 11. Charge distribution of fragments from bifurcation events compared with the distribution observed (Ref. 16) from $^{209}\mathrm{Bi}+\mathrm{p}$, after being mass shifted by $-\Delta A = 11$ and normalized to the peaks.

In an earlier report on a smaller sample of these fission events,[17] we noted that the fission fragments produced in asymmetric fission interacted with a much higher probability than expected than did those produced in symmetric fission. With improved statistics, a difference is still apparent but with marginal significance. If the mean free paths are expressed in Z independent units,[18] then the asymmetric fragments have $\lambda = 0.85 \pm 0.27\bar{\lambda}$, while the symmetric fragments have $\lambda = 2.3 \pm 1.0\bar{\lambda}$. We conclude that there are probably no "anomalous" mean free paths among these fragments.

V. CONCLUSIONS

The bifurcation events observed in emulsion with small ΔZ are consistent with fission of a residual nucleus in flight. The cross section for this process, of $\sigma_{\mathrm{fiss}} = 147 \pm 27$ mb for events with $\Delta Z \leq 5$, is about twice that reported for energetic proton-induced fission.[15] However, for our fission events with $\Delta Z = 0$, i.e., with no emitted protons or helium nuclei, $\sigma_{\mathrm{fiss}} = 44 \pm 15$ mb, less than the proton results at 1 GeV. It is not clear which is the appropriate value for comparison since our results are at all energies less than 1 GeV/nucleon and the proton-induced fission results should include events with $\Delta Z > 0$. Furthermore, the apparent increase in $\langle E_{\perp} \rangle$ as ΔZ increases suggests that the true fission events observed with small ΔZ merge into a class of bifurcation events characterized by significantly increased excitation of the residual nucleus during the initial interaction.

The wide range of asymmetries observed appears contrary to the predictions[19] that asymmetric fission would only be expected at low excitation energies and for nuclei with sufficient mass to close both the 50 and 82 neutron shells. Indeed it has generally been observed[19] that for the fission of nuclei with less than 132 (82 + 50) neutrons, the symmetric-fission mode is dominant. Hence, symmetric fission would also be expected for gold nuclei, particularly since the excitation energies here may well be higher than in the case of low-energy-induced fission. Unfortunately, the gold foil experiments do not appear to address the question of the distribution in S directly, although presumably they could do so with minor modifications. Results with much greater statistical weight than can be obtained in emulsion experiments are needed to study the dependence of S on energy and on projectile type, in order to confirm our observations of the asymmetric fission of gold.

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