Systematics of Some Nucleon Transfer Reactions of Complex Nuclei*

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Nucleon transfer reactions between In^{115} and N^{14} and C^{12} projectiles have been studied at energies up to 10.5 MeV/amu. Radiochemical techniques were used to characterize products resulting from nucleon loss or gain by the target nucleus. Three types of measurements were made: (1) excitation functions; (2) recoil range distributions in the forward direction, by use of stacks of thin catcher foils; (3) average recoil ranges in the forward direction, using thick catcher foils. The recoil measurements provide a clear distinction between transfer and mechanisms involving evaporation from a compound nucleus formed by complete fusion of target and projectile (CFCN). Cross sections are appreciable for transfer of several nucleons, including protons, to the target nucleus. By contrast, reactions in which two protons are lost by the target were not found, although there is considerable probability for loss of as many as five neutrons. A general trend favoring neutron-deficient species is consistent with some secondary neutron evaporation from more highly excited products of primary transfer events. The data indicate that a considerable diversity of transfer reactions occur with appreciable cross section. They thus complement earlier work in which products derived from the projectile were studied. Results are consistent with a concept of grazing reactions in which the Coulomb barrier is penetrated without formation of a compound nucleus by fusion of the reaction partners. The energy dependence of the recoil range of single-nucleon transfer products accords closely with a simple quasielastic collision model. Modification of this model to take mass transfer into account can approximate the recoil behavior of multinucleon pickup products. However, a detailed understanding of multinucleon transfer in grazing reactions is still lacking.

INTRODUCTION

PERHAPS the least understood class of nuclear reactions is that in which two complex nuclei undergo a brief intimate collision without forming a normal compound nucleus. A detailed model of such a reaction cannot be simple: On the one hand, the statistical considerations of normal compound nucleus theory do not apply, and on the other hand, it is difficult to reduce the event to interactions between two or three bodies which remained well defined throughout (as is the case, for instance, in Coulomb excitation).

Such interactions have been characterized as "grazing" collisions.[1] The incident nucleus striking the target on an off-center trajectory penetrates its Coulomb barrier sufficiently for there to be strong nuclear, as well as Coulomb, interaction. But because of excitation in the zone of contact, the nuclear binding is not strong enough to prevent Coulomb and centripetal forces from again separating the system after it has made less than one rotation. During the interaction, there is likely to be nucleon transfer to bound and unbound states.

In postulating the existence of such grazing reactions, Kaufmann and Wolfgang pointed out that although it might be difficult to understand these events in detail, simple theoretical considerations indicate that they should account for a large fraction of total heavy-ion cross sections at higher energies.[1] Various studies have shown that this is indeed the case.[2,3] Thus, although grazing collisions are not simple to understand, they seem to deserve study simply on the basis that they are an important class of nuclear reaction.

The most definitive studies of grazing reactions so far have involved angular distributions of light products, corresponding to projectile residues.[1,4] In the first such study, it was found that light products of nucleon transfer from or to O^{16}, N^{14}, and C^{12} interacting with Rh^{103} peaked at small angles.[1] In addition, single-nucleon transfer products show a peak at larger angles corresponding to the maximum Rutherford scattering angle. This was interpreted to indicate that while single-nucleon transfer products are largely formed by tunneling, in which there is little nuclear overlap, multinucleon transfer usually occurs when there are strong nuclear forces which modify the normal Coulomb trajectory, i.e., in grazing interactions. Lozynski[4] found similar results for the interaction of Ne^{20} with copper and rhodium. With heavier targets, a second peak again appears at larger angles. This is presumably a result of the increasing dominance of Coulomb forces at high Z.

Read *et al.*,[5] have studied the heavy fragments produced in reactions between complex nuclei. They found that the recoil range gave a clear criterion of whether a given product had been formed from a compound nucleus involving complete fusion of projectile and target (CFCN), or by a direct or grazing interaction. While the range of CFCN products increases with

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[1] R. Kaufman and R. Wolfgang, Phys. Rev. 121, 192 (1961).
[2] R. Pfohl, Ph.D. thesis, University of Strasbourg, 1965 (unpublished).
[3] T. Sikkeland, E. Haines, and V. Viola, Phys. Rev. 125, 1350 (1962).
[4] E. Lozynski, Nucl. Phys. 64, 321 (1965).
[5] J. B. J. Read, I. M. Ladenbauer-Bellis, and R. Wolfgang, Phys. Rev. 127, 1722 (1962).

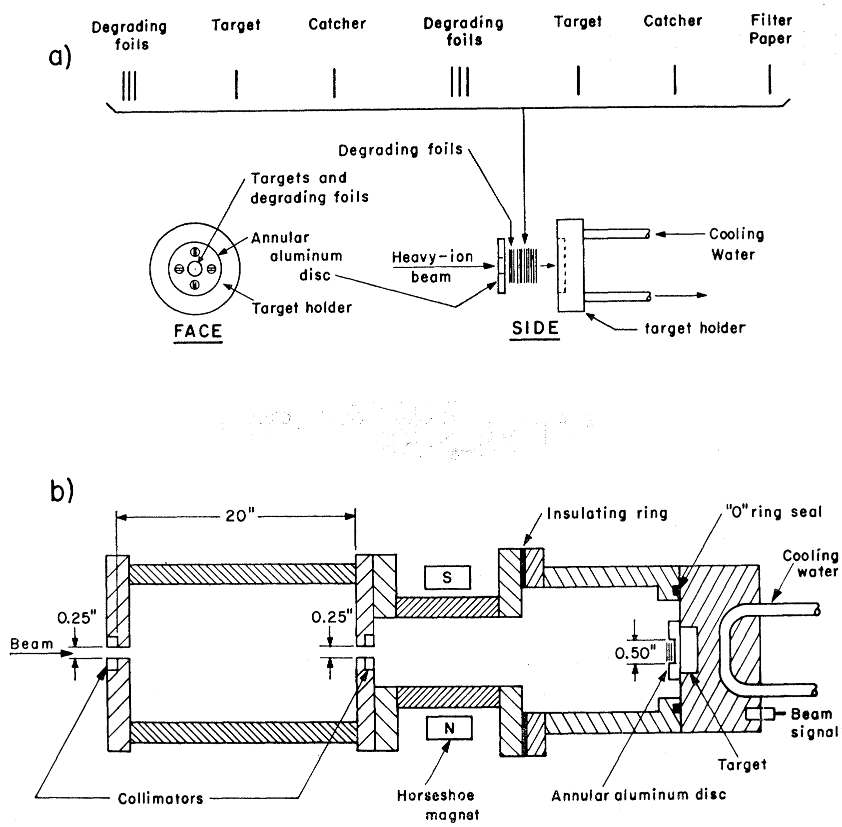

FIG. 1. The target assembly utilized in all bombardments.

bombarding energy, that of nucleon transfer products decreases. However, Read's study and subsequent work by Kumpf and Donets,[6] and by Croft,[7] provide only fragmentary evidence on a few individual products.[8]

In this paper, we report on a more complete survey of heavy products formed by transfer reactions. Such products were characterized by recoil ranges which indicate a non-complete-fusion-compound-nucleus mechanism. Systematics of cross section and recoil-energy behavior provide a basis for some remarks on the kinematics and mechanism of the transfer reactions involved.

The systems $N^{14}+In^{115}$ and $C^{12}+In^{115}$ were chosen because many of the products of nucleon transfer to and from In^{115} have properties making them convenient to assay by radiochemical techniques. Three types of measurements were made.

(1) Determination of recoil range spectra along the beam coordinate. The products were allowed to recoil from a thin target into a stack of aluminum catcher foils thin with respect to their range.

(2) Determination of average recoil range in the beam direction. Products were allowed to recoil from a target into a catcher, both thick with respect to their recoil range The ratio of product in catcher and target can be translated into an average range.

(3) Measurement of excitation functions.

EXPERIMENTAL

All procedures used are described in full detail in the thesis by Strudler[9] and will only be briefly outlined here. The Yale heavy-ion accelerator was used to provide C^{12} and N^{14} beams of 10.5 ± 0.2 MeV/amu. Lower energy particles were produced by passage of the beam through calibrated aluminum foils of proper thickness, as calculated using Northcliffe's range-energy data.[10] Standard monitoring techniques were used to determine beam intensity. The target assembly is shown in Fig. 1.

In experiments measuring the average recoil range, the indium targets had a thickness of 1.5–4 mg/cm², always greater than the recoil range in question, but not so thick as to unduly broaden the energy spectrum of collisions. Products recoiled into aluminum catchers 0.8 mg/cm² thick. The average range of a specific

[6] H. Kumpf and E. D. Donets, Zh. Eksperim. i Teor. Fiz. 44, 798 (1963) [English transl.: Soviet Phys.—JETP 17, 539 (1963)].

[7] P. D. Croft, Lawrence Radiation Laboratory Report No. UCRL 11563, 1964 (unpublished).

[8] J. Alexander and L. Winsberg [Phys. Rev. **121**, 529 (1961)] have reported that the reactions Au^{197}(O^{16}, $2pxn$ and $3pxn$) could not be accounted for by a compound nucleus mechanism, implying that they are formed by transfer of many nucleons. However, this conclusion was based on the observation of a 13% deficiency in momentum transfer relative to compound nucleus formation, an effect not large compared to the inherent uncertainty of the method.

[9] P. M. Strudler, Ph.D. thesis, Yale University, 1965 (unpublished).

[10] L. C. Northcliffe, Ann. Rev. Nucl. Sci. **13**, 67 (1963).

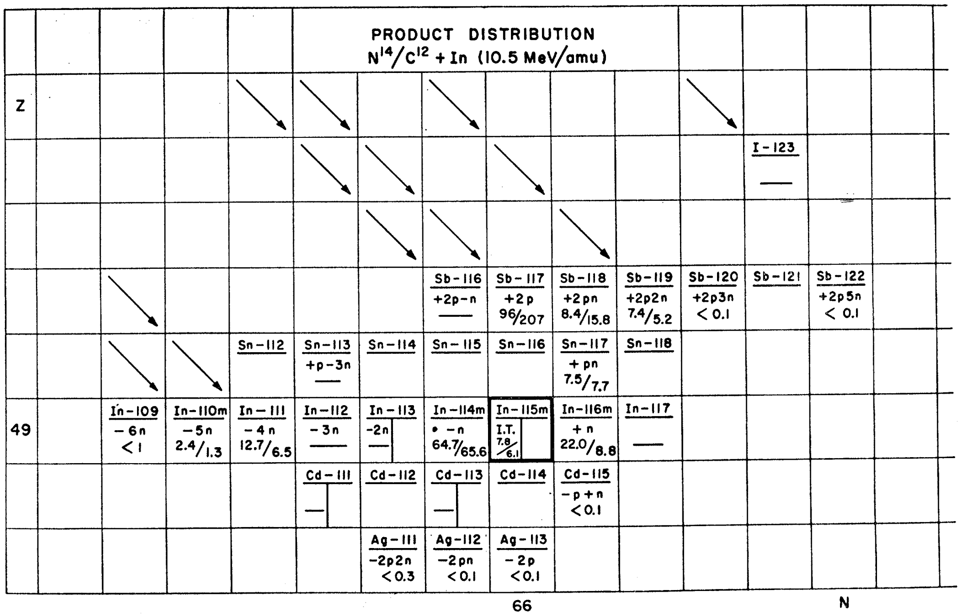

FIG. 2. Summary of the products surveyed. Yields at 10.5 MeV/amu for both C^{12} and N^{14} are indicated. The target nucleus is framed. Arrows indicate other species having beta-decay half-lives short or comparable to bombardment and separation times used. If formed, these will contribute to the measured yields of the nuclides indicated.

product R is then given by $R=fW$, where f is the fraction of activity recoiling forward out of the target and W is the thickness of the target.

In experiments measuring the differential recoil range spectra, indium targets 75-200 μg/cm^2 thick backed by a stack of aluminum catchers 120–200 μg/cm^2 thick were used.[11] Experimental procedures followed were essentially those described by Read *et al.*[5]

Separation of products employed standard radiochemical techniques. Assay of the invididual products was primarily by gamma-ray spectroscopy. Knowledge of the decay schemes involved and calibration of the counting apparatus made it possible to determine absolute cross sections.

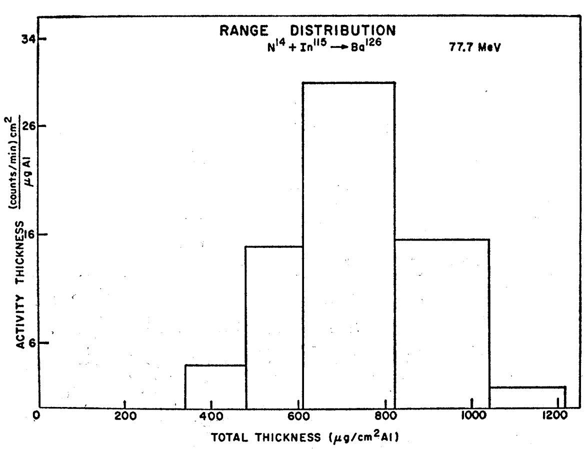

FIG. 3. Differential range distribution of Ba^{126} recoils in aluminum from the reaction $In^{115}(N^{14},3n)Ba^{126}$ at 77.7 MeV. The experimental average range 0.74 mg/cm^2 In. The straggling parameter found, 0.22, is consistent with Ref. 13.

[11] Obtained through the kindness of J. Alexander.

The magnitude of errors is indicated in the figures showing the results. As plotted, the excitation functions and recoil ranges show error bars in both horizontal and vertical dimensions. The horizontal uncertainty represents the degradation of beam energy in passing through the target. In addition, there may be systematic errors of up to 5–6% due to beam straggling in the degrading foils, the accuracy of the Northcliffe range-energy data, and the uncertainty in the beam energy emerging from the accelerator. The vertical error bars represent estimated standard deviations in cross sections. These include uncertainties in (1) flux measurement (3%); (2) target thickness (5%); (3) chemical yield (5%); (4) crystal efficiency (5%); and (5) photopeak intensity (5–20%).

In most experiments, natural indium containing 4.72% In^{113} was used. A bombardment of 99.9% In^{115} with 138 MeV N^{14} gave yields of In^{110m}, In^{111}, In^{114m}, In^{115m}, and In^{116m} which were the same within a few percent as those obtained in a similar experiment with natural indium. We conclude, therefore, that results on

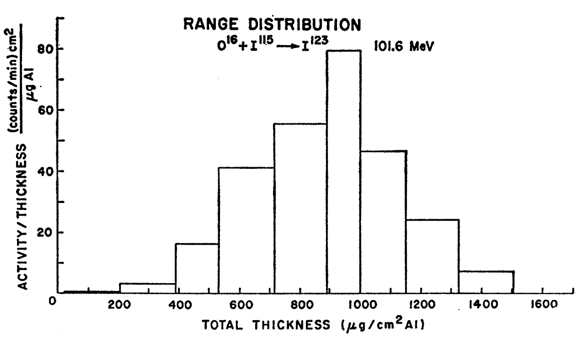

FIG. 4. Differential range distribution of Io^{123} recoils in aluminum from the reaction $In^{115}(O^{16},4p4n)I^{123}$ at 101.6 MeV.

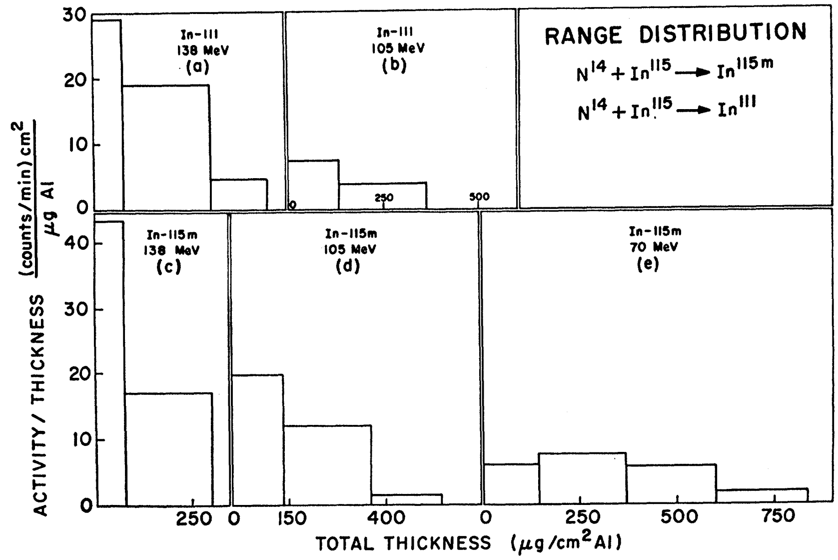

FIG. 5. Differential range distributions of In^{111} and In^{115m} recoils in aluminum from the reaction of $N^{14}+In^{115}$ at 138, 105, and 70 MeV.

natural indium may be taken as representing, within experimental error, reactions with In^{115} only.

Range-Energy Relations

In the interpretation of experimental data, we have used relationships between recoil energy and recoil range based on the theoretical treatment of Lindhard, Scharff, and Schiott (LSS).[12] The validity of this relationship was tested by measuring the range of $In^{109,110m,111}$ produced by 147-MeV N^{14} bombardment of natural molybdenum. These products would be expected to derive by evaporation of several neutrons from a compound nucleus formed by complete fusion. Their recoil energy may thus be predicted with some assurance by use of the formula

$$E_r = E_b A_b A_r / (A_b + A_t)^2 , \qquad (1)$$

where E and A are energy and mass and the subscripts b, r, and t refer to the bombarding, recoil, and target nuclei, respectively. The recoil ranges calculated from this energy agree with those actually measured within the relatively large experimental error stemming from the thickness (7.77 mg/cm^2) of the Mo foil.

A better test was provided by the differential ranges of Ba^{126} and I^{123} from bombardment of In^{115}. As discussed below, these agreed within a few per cent with LSS ranges calculated assuming a complete fusion compound nucleus mechanism. Full details may be found in the thesis by Strudler.[9]

RESULTS AND DISCUSSION

Figure 2 provides a summary of the products and reactions surveyed. Yields at 10.5 MeV/amu for both C^{12} and N^{14} are indicated; a dash means no measurement was made. Arrows show the cases where beta decay of a precursor contributes to the measured product.

Complete Fusion Compound Nucleus Versus Transfer Products

As in the earlier work,[5] it was found that the differential range experiments provide an unambiguous distinction between product formation by each of the two general types of mechanisms. Figure 3 for $In^{115}(N^{14},3n)Ba^{126}$, and Fig. 4 for $In^{115}(O^{16},4p4n)I^{123}$, are indicative of formation through an intermediate formed by complete fusion of projectile and target (CFCN). The average ranges agree within a few percent with those calculated using Eq. (1) (which assumes CFCN) and the LSS range-energy relation (see Fig. 3 caption). The distributions are Gaussian in shape, and the straggling parameters are reasonable considering the straggling of monoenergetic recoils and also the finite thickness of the target.[5,12,13]

Figures 3 and 4 show no contribution whatever by any mechanism in which less than full momentum is

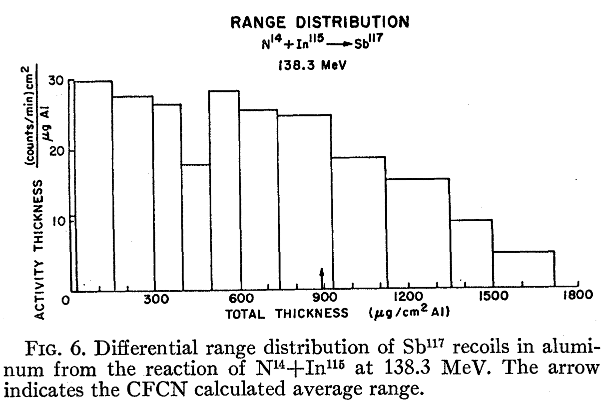

FIG. 6. Differential range distribution of Sb^{117} recoils in aluminum from the reaction of $N^{14}+In^{115}$ at 138.3 MeV. The arrow indicates the CFCN calculated average range.

[12] J. Lindhard, M. Scharff, H. E. Schiott, Kgl. Danske Videnkab. Selskab, Mat. Fys. Medd. 33, No. 14 (1963).

[13] M. Kaplan and R. D. Fink, Phys. Rev. **134**, B30 (1964).

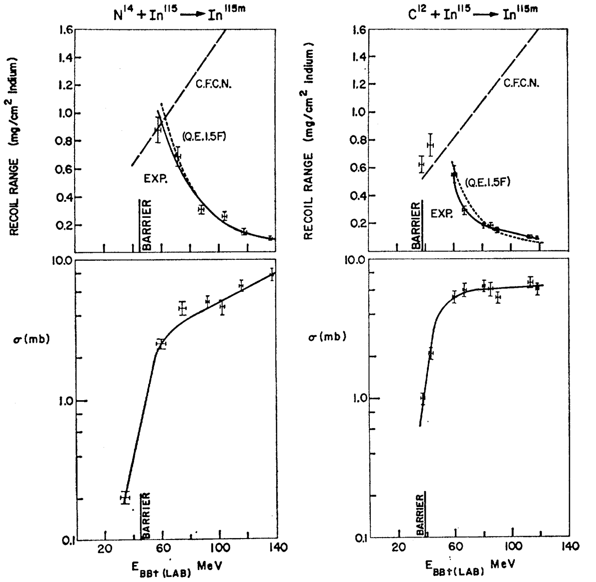

FIG. 7 Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115} \rightarrow In^{115m}$, and $C^{12}+In^{115} \rightarrow In^{115m}$.

transferred by the projectile. This is in sharp contrast with Fig. 5 showing the recoil distribution from the reactions $In^{115}(N^{14},\ )In^{115m}$ and $In^{115}(N^{14},\ )In^{111}$. The latter type of distribution has been shown[5] to be characteristic of transfer reactions. [For present purposes, the reaction $In^{155}(N^{14},\ )In^{115m}$ may be considered as a limiting case of transfer reaction where the nucleon gain by the target is zero and excitation is the only net result.]

Figure 6 represents a mixed case, $In^{115}(N^{14},\ )Sb^{117}$ where the product appears to be formed both by a transfer mechanism and by evaporation from CFCN. This situation has a precedent in the study of the reaction $Co^{59}(O^{16},\ )Cu^{61}$.[5]

In this study, we have found that, with certain clear exceptions, most products with a mass near that of the target have transfer-type recoil ranges. This was expected. The formation of these products by evaporation from a CFCN is generally unlikely in view of the excitation energies available and the preference for the emission of neutrons rather than protons.

Target Excitation and Single-Neutron Transfer

Figure 7 shows the excitation functions and average forward recoil ranges of In^{115m} which has been excited by interaction with C^{12} and N^{14}. Figures 8 and 9 show the same for the various single-nucleon transfer reactions which were observed.

These excitation functions show the usual shapes associated with transfer mechanism: a sharp rise in the vicinity of the Coulomb barrier followed by a slower rise, or a leveling off at higher energies. In no case is a maximum observed. It should be noted that these excitation functions, and others to be discussed later, may contain contributions from processes involving emission of free nucleons, either during the primary event or by subsequent evaporation. For instance, the high yield of In^{114m} may, in part, be the result of Coulomb excitation of In^{115} to unbound states.

It is interesting to note that cross sections for production of In^{116m} are greater in the case of N^{14} than they are in the case of C^{12}. This may de due to the fact that the least tightly bound neutron in $N^{14}(P_{1/2})$ requires 8.2 MeV less energy to be removed than the least-tightly bound neutron in $C^{12}(P_{1/2})$. Both Kaufman and Wolfgang[1] and Pomorski[14] *et al.*,[15] have previously shown that nucleon transfer cross sections have such a dependence on the binding energy of the last nucleon.

The recoil range plots are of considerably more interest, although in many cases, low cross sections precluded meaningful measurement at the lowest energies. On each graph, there is plotted the recoil range to be expected from the CFCN mechanism, as calculated using Eq. (1). Quite obviously, this type of process makes little contribution.

Whereas, the recoil range to be expected from a CFCN mechanism is well defined, the ranges of transfer products will depend on the details of the actual transfer process involved. In all plots, we indicate the prediction of a well-defined extremal dynamic model: a quasielastic (q.e.) interaction in which the recoil of the products is essentially that of two bodies which undergo a pure Coulomb elastic interaction. This, of course, represents an idealized situation, since the events observed are obviously inelastic. Yet where the mass and

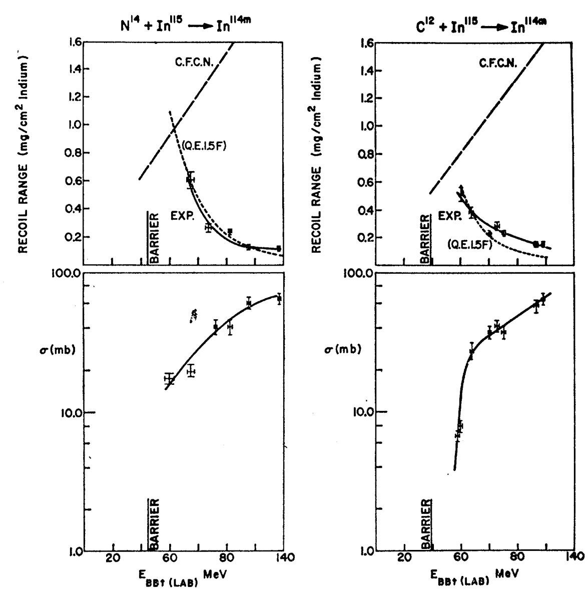

FIG. 8. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115} \rightarrow In^{114m}$, and $C^{12}+In^{115} \rightarrow In^{114m}$.

[14] L. Winsberg and J. M. Alexander, Phys. Rev. **121**, 518 (1961).
[15] L. Pomorski, J. Tys, V. V. Volkov, J. Wilczynski, in *Proceedings of Third Conference on Reactions between Complex Nuclei, Asilomar* (University of California Press, Berkeley, 1963).

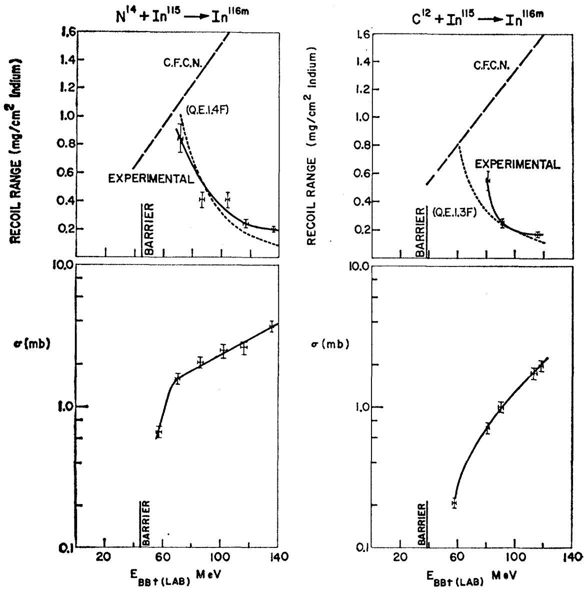

FIG. 9. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115}\rightarrow In^{116m}$, and $C^{12}+In^{115}\rightarrow In^{116m}$.

energy transferred are small fractions of the total involved, elastic Coulomb forces could dominate the kinematics of the recoil.

Calculation of the recoil range according to the quasielastic model was made as follows: reaction is assumed to occur at a certain distance of closest approach, $R_{\min}$, which is not within the Coulomb barrier. If the energy and mass transfer are small, the Rutherford scattering relationship can then be used to approximate the angle θ through which the projectile is scattered in the center-of-mass system

$$R_{\min}=Z_1Z_2e^2/2E_{\mathrm{c.m.}}(1+\csc\tfrac{1}{2}\theta) \qquad (2)$$

(where the terms have their usual meaning).

From the angle θ, the angles at which the projectile and target recoil in the laboratory system can be calculated. Applying the two equations governing conservation of momentum in an elastic collision, the recoil energy of the target (actually the heavy product) is determined. The recoil range may then be obtained by use of the LSS range-energy relations. From this and the angle of recoil, the projection of the range in the beam direction can be calculated. This quantity may be compared to the experimental average recoil range in the forward direction and is recorded on the figures as the q.e. curve.

The only variable in this calculation is $R_{\min}$, which can be expressed in terms of the usual reduced radius, r_0

$$R_{\min}=r_0(A_1^{1/3}+A_2^{1/3}). \qquad (3)$$

In Figs. 7–14, the r_0 has been chosen to be the commonly used value of 1.5 F.

The quasielastic calculation fits not only the shape but the magnitude of the range plots for $In^{114m,\,115m,\,116m}$ quite well. The indicated dominance of Coulomb forces is reasonable. For In^{115m} produced by Coulomb excitation, it could hardly be otherwise. It is interesting to note that for this process, the value of the reduced radius which gives the best fit is 1.5 F.

For the reactions leading to In^{114m} and In^{116m}, the good fit is also to be expected since the major mechanism of single nucleon transfer appears to be tunneling—a good quasielastic process. Angular distribution of projectiles which have lost one neutron have their largest peak at the angle predicted by Eq. (2)[16–18] (indicating that in most such events, there has been no appreciable penetration of the Coulomb barrier). It would, therefore, be quite odd if this same equation did not also describe the behavior of the complementary heavy product in what appear to be completely analogous systems.

The values of r_0 deduced from angular distributions of the stripped projectiles are between 1.55 and 1.65 F.[1] The best fits to our data are for $r_0=1.5$ F or possibly less. In view of the experimental uncertainty, it is difficult to say whether there is a real difference. However, some apparent "discrepancy" is to be expected between the present data and that part of the angular distributions of the light fragments which correspond to tunneling. It has been shown that neutron-stripped projectiles have a second, generally smaller, peak at more forward angles. This has been attributed to the grazing mechanism which, because of the greater importance of nuclear forces, will be less well approximated by the quasielastic models (see below). In the

[16] R. Kaufman and R. Wolfgang, Phys. Rev. **121**, 206 (1961).

[17] J. A. McIntyre, T. L. Watts, and F. C. Jobes, Phys. Rev. **119**, 13331 (1960).

[18] J. M. Strutinskii, Zh. Eksperim. i Teor. Fiz. **46**, 2078 (1964) [English transl.: Soviet Phys.—JETP **19**, 1401 (1964)] has developed a treatment which enables him to fit any given angular distribution by choice of a suitable dependence of the intensity of reaction as a function of the channel of orbital angular momentum l. In discussing this work, he states "The scattering angle is not uniquely related to the impact parameter, and therefore it is not possible to recalculate the angular distribution to give the distribution of impact parameters," as was done in Refs. 16 and 17. This statement is, of course, a truism in the sense that insofar as any scattering event is a quantized process, the uncertainty principle makes it impossible to associate any given angle with a precisely defined impact parameter. However, Strutinskii's article is sometimes interpreted as implying that the use of angular distributions to provide any measure of the extent of barrier penetration (as in Refs. 16, 17, and 1) is meaningless. A careful examination shows that any such implication is unwarranted. Strutinskii's treatment shows that if a sufficiently wide range of orbital angular momenta Δl is involved, the trajectory becomes essentially classical. The relevant statement of the uncertainty principle is $\theta\Delta l>2$ where θ is the classical scattering angle. Only when this quantity is exceeded, can the classical peak corresponding to tunneling appear. Strutinskii's analysis further shows that for the work in Ref. 17, $\theta\Delta l$ is typically 4. Thus by the correspondence principle, a classical description is justified, and it is meaningful to distinguish between events in which there is appreciable penetration of the Coulomb barrier (grazing collisions) and those in which there is not (tunneling).

Strutinskii's treatment can be of considerable value in providing an approximate measure of the range of angular momenta Δl involved in the processes observed. However, beyond confirming their nature as surface reactions, it can in itself provide no further direct indication of the interaction potential or mechanism.

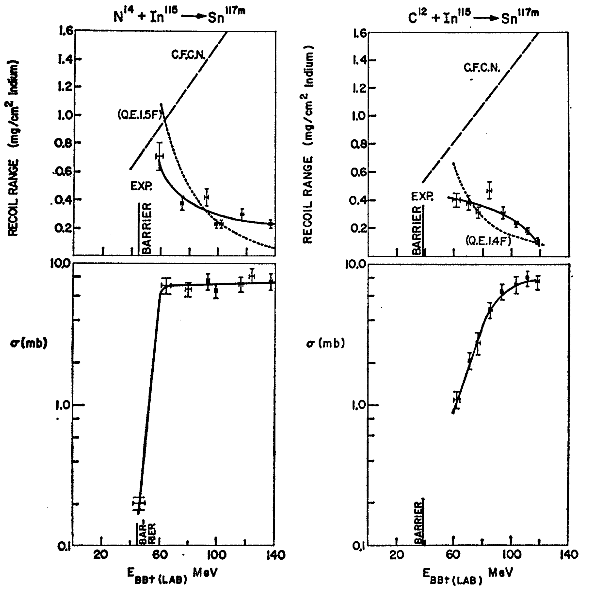

FIG. 10. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115}\to Sn^{117m}$, and $C^{12}+In^{115}\to Sn^{117m}$.

grazing mechanism, more momentum will be transferred than in pure Coulombic events. Recoil ranges would, therefore, tend to be greater than that predicted by quasielastic scattering [Eq. (2)] using distances of closest approach derived from tunneling.

This is indeed what appears to be observed in several cases. In particular, the reaction $In^{115m}(C^{12},\ )In^{116m}$ (Fig. 9) seems to give an appreciably greater average recoil range to the In^{116m} than that predicted by the q.e. ($r_0=1.5$ F) calculation. It is interesting to note that the analogous (C^{12},C^{11}) reaction on Rh^{103} gives an angular distribution of the C^{11} in which the small-angle, grazing peak is unusually large compared with the tunneling peak.[1] This would be reflected as a somewhat greater average forward range of the corresponding heavy product—which is just what is observed. The explanation previously advanced[1] for the indicated high ratio of grazing to tunneling interactions in (C^{12},C^{11}) reaction involves the high binding energy for the last neutron in C^{12}.

Two-Nucleon Gain by Target

Figure 10 shows excitation functions and average recoil ranges for the formation of Sn^{117} by bombardment of In^{115} with N^{14} and C^{12}. Neither excitation functions nor recoil ranges show any indication of appreciable contribution by CFCN mechanism. Cross sections for such *pn* or deuteron pickup processes by the target are appreciable, being quite comparable to those for single neutron pick-up but smaller than those for neutron loss.

There is a very striking difference in the shapes of excitation functions for producing Sn^{117m} by $C^{12}$and N^{14}. The sharp rise of the N^{14} function near the barrier is probably associated with the relatively easy transfer of a deuteron cluster from this nucleus. Such differences in the ease of deuteron transfer from N^{14} as compared to C^{12} have been found in other systems.[19]

The average range curves follow the quasielastic calculations, but in general not as well as do those for single-nucleon stripping from the target. This is not unexpected since tunneling is probably a minor mechanism for two-nucleon transfer, most of this process probably occurring in a more intimate grazing collision.

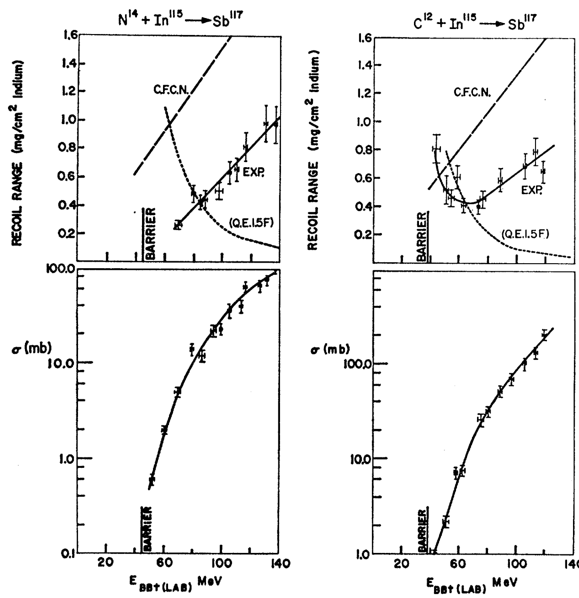

FIG. 11. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115}\to Sb^{117}$, and $C^{12}+In^{115}\to Sb^{117}$.

Figure 11 shows the yield of Sb^{117} which may be produced by transfer of two protons from C^{12} and N^{14} projectiles to In^{115}. The behavior observed here is similar in all respects to the analogous $Co^{59}(O^{16},\ )Cu^{61}$ reactions previously studied.[5] The continued rapid rise of the excitation functions even at the highest energies suggests that a mechanism other than transfer is contributing. This was confirmed by the finding of large amounts of Te^{117} as a product of reaction of C^{12} and N^{14} with In^{115}. The Te^{117} decays to Sb^{117} with a half-life of 60 min.[20]

At high bombarding energies, Te^{117} is a plausible product of evaporation from a complete fusion compound nucleus. The important contribution of such a mechanism to the Sb^{117} yield is reflected in the sharp rise in the average ranges (Fig. 11) at higher bombardment energies. Strong confirmatory evidence for this postulate is to be found in the differential range plot

[19] C. D. Zafiratos, Phys. Rev. **136**, B1279 (1964).

[20] To normalize the Te^{117} contribution to the Sb^{117} yield irradiation times were fixed at 60 min with tellurium being scavenged from the product 30 min after the end of the irradiation and prior to separation of Sb^{117}. Any Sb^{117} formed by decay of Te^{117} prior to the scavenging step is included in the cross sections quoted.

(Fig. 6) which indicates comparable contributions from both direct transfer and CFCN mechanisms.

The ranges of Sb^{117} from $In^{115}(C^{12},\ )Sb^{117}$ could be measured to low energies where the CFCN mechanisms should no longer contribute. Here the increase of recoil range with decreasing beam energy characteristic of transfer reactions is found.

Two-neutron capture by the target was not studied because of the analytical difficulty of resolving the short-lived gamma rays characteristic of the product.

Multinucleon Gain by Target

Figure 12 shows the production of Sb^{118} by $2pn$ pickup by In^{115} from C^{12} and N^{14}. The considerable cross sections observed appear to be largely due to transfer processes. Sb^{118} has no short-lived precursor decaying into it. Its direct formation through CFCN requires evaporation of four or five protons and has been estimated to occur with small cross section.[21] Certainly the average recoil ranges are much smaller than they would be if there were dominant contributions by CFCN mechanisms.

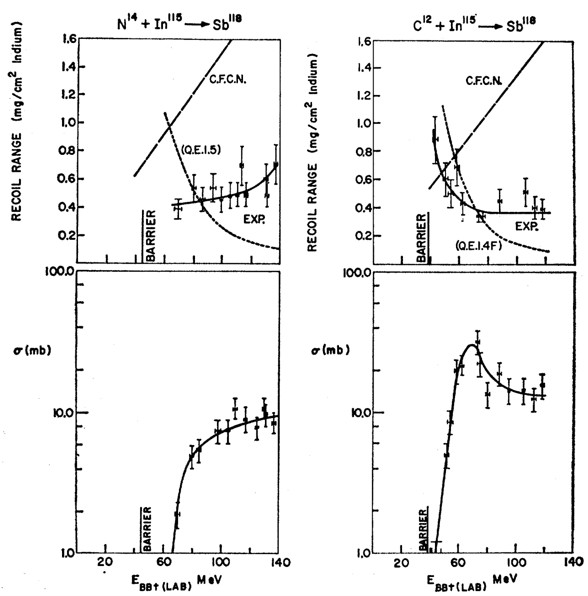

FIG. 12. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115} \rightarrow Sb^{118}$, and $C^{12}+In^{115} \rightarrow Sb^{118}$.

In the case of $In^{115}(C^{12},\ )Sb^{118}$ where recoil ranges were measured to low energies, the typical upward hook characteristic of these transfer reactions is observed. In both cases, the average ranges at higher energies are significantly larger than the q.e. predictions. The possibility that this could be due to a contribution by a CFCN mechanism is unlikely, although it cannot be excluded on the basis of calculations[21] alone. Unfortunately, differential range spectra which could have eliminated this possibility could not be obtained. Nevertheless, the most likely cause of these increased ranges is that a grazing collision in which there is net transfer of three or more nucleons imparts considerably more momentum than does a quasielastic interaction.

The peak at 70 MeV in the $In^{115}(C^{12},\ )Sb^{118}$ excitation function may be due to transfer of an alpha particle with subsequent evaporation of a neutron. It requires only 7.4 MeV to separate an alpha particle from C^{12}. An alpha particle transferred from a 70 MeV C^{12} might be expected to carry about 20-MeV excitation energy into the target—enough to evaporate a neutron. The fact that the $In^{115}(C^{12},\ )Sb^{118}$ reaction peaks at 19 MeV is quite suggestive in this connection.[23]

Figure 13 shows production of Sb^{119} by a net gain of two protons and two neutrons from the target. Again, appreciable cross sections are found. The relatively sharp rises in both excitation functions and, more definitely, in the average range plots of higher energies suggest that there may be considerable contribution through a CFCN mechanism. Presumably, most of this results from beta decay of precursors to Sb^{119}. At lower energies, however, the increase in range with decreasing bombardment energy indicative of a transfer mechanism is apparent.

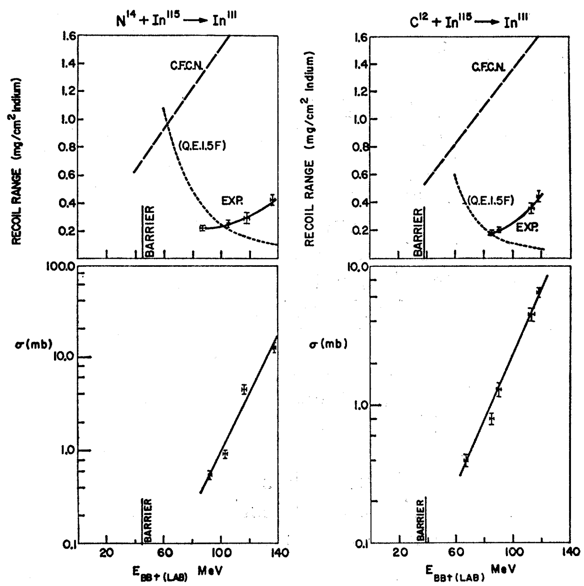

FIG. 13. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115} \rightarrow Sb^{119}$, and $C^{12}+In^{115} \rightarrow Sb^{119}$.

[21] Black (Ref. 22) has calculated the product distribution arising from evaporation by the high angular momentum compound nucleus formed in the reaction of $B^{11}+Cd^{116}$. A Monte Carlo method was employed to determine the partial widths for multineutron or proton emission from the compound nucleus. The cross-section data were fitted by assuming that the Weisskopf level density $W(E,J)$ is decreased by the amount of energy available only for rotation of the compound nucleus. His method of calculation was applied to the $C^{12}+In^{115}$ system and suggests that a negligible fraction of the CFCN decay to antimony isotopes.

[22] R. Black, Ph.D. thesis, Massachusetts Institute of Technology, 1964 (unpublished).

[23] G. M. Temmer, Phys. Rev. **76**, 424 (1949).

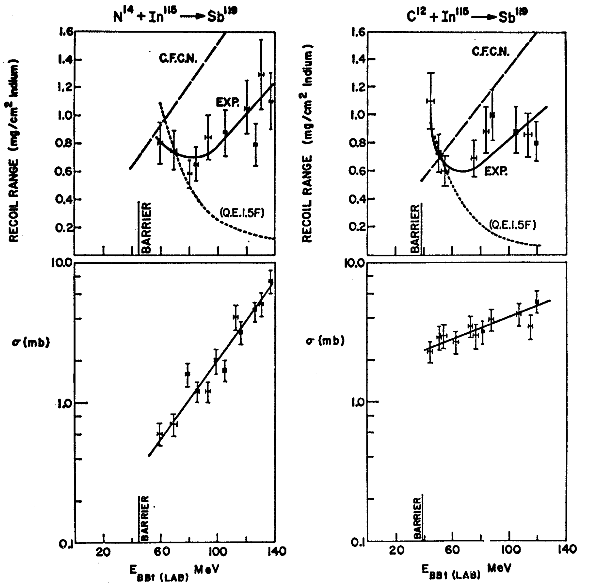

FIG. 14. Excitation functions and average forward recoil ranges for the reactions $N^{14}+In^{115}\rightarrow In^{111}$, and $C^{12}+In^{115}\rightarrow In^{111}$.

A search for $2p3n$, $2p5n$, $2p7n$ transfer to the target indicated that for full energy C^{12} and N^{14} the corresponding antimony isotopes have yields of less than 100 μb.

Nucleon Loss from Target

Despite the appreciable cross sections for $2p$, $2pn$, and $2p2n$ gain by the target, it was found that corresponding loss of $2p$, $2pn$, and $2p2n$ to form $Ag^{113,112,111}$ has cross sections of less than 100 μb for both C^{12} and N^{14} at 10.5 MeV/amu. This is consistent with the earlier work of Grochulski[24] on $Ne^{20}+Ta^{181}$ in which it was found that cross sections for a large variety of multiproton loss products were less than 100 μb.

Sachs *et al.*[25] and Birnbaum[26] have shown that high-energy neutron and deuteron transfer into light nuclei can be inhibited if the angular momentum of the level being populated does not match that which is transferred in the reaction. Thus, inhibition of nucleon transfer from a heavy nucleus (target) to a light one (projectile) may derive from the relatively low density of levels of high angular momentum in the low mass nuclei into which the transferred particles may be placed.

However, multineutron loss from the target is observed in appreciable cross section. Measurements of two and three neutron loss could not be made, but Fig. 14 and Table I show that 4 and 5 neutron loss is quite significant at higher energies.

The data on average ranges show clearly that these products cannot be accounted for by CFCN mechanisms. Yet the excitation functions do not rise sharply at the Coulomb barrier and then plateau, as is characteristic of most transfer reactions. Rather, their rise at higher energies suggests that some internal energy threshold, as is usual when there is evaporation, must be reached. This suggests the existence of a two-step mechanism: In the primary reaction, the target may lose neutrons, but, in any case, it is strongly excited. It subsequently evaporates neutrons to form the final product. That grazing reactions may leave the transfer product sufficiently excited to evaporate nucleons has been pointed out in the original formulation of this general mechanism.[1] As has been mentioned earlier in this article, such evaporation may also occur in some of the events in which there is a net gain of nucleons by the target. The Coulomb barrier will, of course, favor emission of neutrons rather than protons. Such secondary evaporation will therefore favor those final products of transfer reactions which are neutron deficient. An inspection of Fig. 2 suggests that this is indeed the case.

Related studies in our laboratory[27] provide compelling evidence for such secondary evaporation of neutrons from the primary products of transfer reactions in the similar system $Cs^{133}+N^{13}$. Conservation conditions were applied to angular distributions and differential range data on cesium isotopes which have lost several neutrons. The results suggest that these were largely formed by evaporation from an intermediate which had lost two neutrons in a direct transfer process.

Charge Exchange

The only other transfer reaction that was searched for was neutron-proton exchange between target and projectile to yield Cd^{115}. With C^{12} and N^{14} at 10 MeV/amu, this process was found to have a cross section not greater than 100 μb.

Dynamics and Mechanism

At this point, a brief reconsideration of the dynamics of transfer reactions is appropriate. As has been seen, the quasielastic formalism provides a good representation of the recoil behavior of target nuclei which have

TABLE I. cross sections and average recoil ranges for In^{110m}.

Projectile	Beam energy (MeV)	Cross section (mb)	Recoil range (mg/cm² of In)
N^{14}	138.2–135.8	2.4	0.36
N^{14}	120.4–151.9	0.63	0.36
C^{12}	119.2–117.1	1.3	0.37
C^{12}	115.2–111.6	0.7	0.39

[24] W. Grochulski, T. Kwiecinska, L. Go-Chan, E. Lozynski, J. Maly, L. K. Tarasov, and V. V. Voklov, in *Proceedings of the Third Conference on Reactions between Complex Nuclei, Asilomar* (University of California Press, Berkeley, 1963).

[25] M. Sachs, C. Chasman, and D. A. Bromley, Phys. Rev. **139**, B92 (1965).

[26] J. Birnbaum, Ph.D. thesis, Yale University, 1965 (unpublished).

[27] R. Morse and I. L. Preiss, Phys. Letters, **20**, 509 (1966); also Phys. Rev. (to be published).

been excited or which have lost a single neutron. When there is appreciable mass transfer to the target, then, regardless of the mechanism, the quasielastic model can no longer provide a good approximation.

The quasielastic treatment can be extended to cases where there is mass transfer to the target by a procedure which is sufficiently simple to be worth considering. In a reaction in which x neucleons are transferred, we assume: (1) that the x nucleons bring into the target a momentum corresponding to a fraction x/A_b of the momentum of the projectile (where A_b is the mass of the projectile); (2) that the residue of the projectile, having a mass (A_b-x) undergoes quasielastic scattering with the target, at radius $R_{\min}$, as was previously assumed for the entire projectile. The product then receives two components of momentum, one in the forward direction from absorbing the transferred nucleons, and the other at some definite angle from the Coulomb interaction with the projectile residue. From these the recoil energy and angle are evaluated, and then using the LSS treatment, the corresponding recoil range.

Figure 15 shows the projection of the range in the forward direction as predicted by this model of transfer reaction. At higher energies, these ranges are larger than the quasi-elastic ranges but smaller than the CFCN ranges. Near the barrier, they are shorter than q.e. ranges and greater than CFCN ranges.

There is considerable correspondence, both as to shape and magnitude, between these theoretical range functions and the experimental data for production of Sn^{117m} and Sb^{118} (those products which are likely to be pure transfer products, with no CFCN contribution. See Figs. 11 and 12). In principle, by comparison of such calculated and experimental plots, it should be possible to estimate how many nucleons were transferred and how many subsequently evaporated. However, neither the precision of the experiments not the nature of the assumptions of the dynamic model warrant the drawing of conclusions at this level of detail.

Reactions in which nucleons were transferred from the target are not within the scope of this model. Not surprisingly, the experimentally observed range functions for In^{111} do not resemble those calculated.

The results obtained here are in general accord with the grazing model of nuclear reactions. The products observed are clearly not the result of a complete fusion compound nucleus mechanism, and, except in the cases of zero and single nucleon transfer, they are difficult to account for in terms of Coulomb excitation or tunneling.

Grazing nuclear reaction can be defined as a superficial contact between two complex nuclei in which there is considerable overlap of the nuclear potential wells without formation of a compound nucleus. This concept is, however, too general to provide a quantitative understanding of the details of the process. The grazing mechanism suggests that during the collision the many-body system formed cannot be expected to have a uniform temperature.[1] Thus normal statistical considerations applicable to quasi-equilibrium systems cannot be readily applied. On the other hand, the system is too complex to be easily treated in terms of two or three body interactions. These factors make it difficult to provide an adequately detailed model of what is obviously a significant class of nuclear reactions.

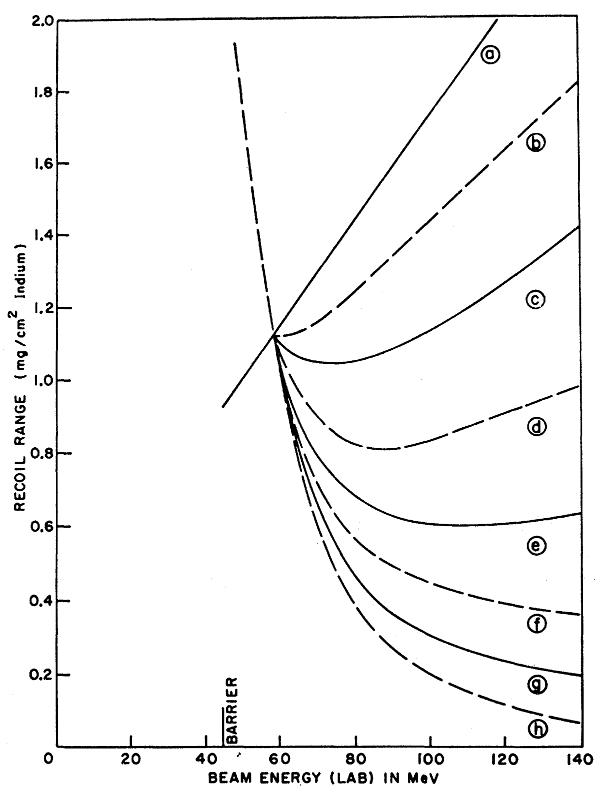

FIG. 15. Average recoil ranges calculated from the partial absorption + quasielastic scattering treatment for $N^{14}+In^{115}$. The individual curves show: (a) complete absorption; (b) C^{12} absorbed, d scattered; (c) B^{10} absorbed, He^4 scattered; (d) Be^8 absorbed, Li^6 scattered; (e) Li^6 absorbed, Be^8 scattered; (f) He^4 absorbed, B^{10} scattered; (g) d absorbed, C^{12} scattered; (h) quasielastic scattering. An $r_0=1.5$ F was employed in the quasielastic calculation.

ACKNOWLEDGMENTS

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