Mechanisms of heavy-ion induced (p, n)- and (n, p)-type reactions*

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Excitation functions and recoil ranges for the reactions ^{65}Cu(^{12}C, X)^{65}Zn and ^{65}Cu(^{11}B, X)^{65}Zn were measured for ^{12}C ion energies between 43 and 122 MeV and for ^{11}B ion energies between 60 and 115 MeV. The angular distribution for the production of ^{65}Zn by the ^{65}Cu(^{12}C, X)^{65}Zn reaction was determined at 88.6 MeV. The forward projected recoil ranges are not in satisfactory agreement with ranges which would be predicted on the basis of the complete fusion compound nucleus mechanism nor apparently with a simple kinematic treatment of the quasielastic scattering model. The experimental results appear to be consistent with a charge-exchange or nucleon transfer mechanism in which the distance of closest approach varies inversely with incident energy. Evidence for the enhancement of isospin $\Delta T = 0$ transitions to target analog states is suggested in that only an upper limit could be placed on the production of cross sections of ^{65}Ni, a $\Delta T \neq 0$ product, compared to high yields for ^{65}Zn, a $\Delta T = 0$ product.

[NUCLEAR REACTIONS ^{65}Cu(^{12}C, X)^{65}Zn, ^{65}Cu(^{12}C, X)^{65}Ni, ^{65}Cu(^{11}B, X)^{65}Zn, ^{65}Cu(^{11}B, X)^{65}Ni; separated isotope targets, $E(^{12}\text{C}) = 43$–122 MeV, $E(^{11}\text{B}) = 60$–115 MeV; measured $\sigma(E)$, recoil fragment (E), and fragment $\sigma(\theta)$ for 88.6 MeV ^{12}C.]

INTRODUCTION

In 1960 Pinajian[1] reported results which suggested simultaneous transfer of a proton (or neutron) to the target from the projectile and a neutron (or proton) to the projectile from the target. In particular, he examined a reaction which he described as ^{27}Al(^{14}N, ^{14}O)^{27}Mg. The ^{27}Mg was radiochemically determined but no attempt was made to investigate the production of ^{14}O. If the reaction actually occurs via the direct emission of ^{14}O, then there are two possible descriptions of the mechanisms involved: (i) double transfer or nucleon switching, as described above or (ii) a charge exchange mechanism.

In recent years, as the interest in transfer reactions developed,[2-6] a number of investigations of the products potentially resulting from charge exchange have been reported. Strudler, Preiss, and Wolfgang[7] examined reactions which would be the equivalent of those suggested by Pinajian, namely ^{115}In(^{12}C, ^{12}N)^{115}Cd and ^{115}In(^{14}N, ^{14}O)^{115}Cd. In neither case was the cross section greater than 100 μb.

More recently Galin *et al.*[8,9] have attempted to determine projectile residues using a counter telescope. With silver as a target, they examined the reactions (^{12}C, ^{12}B), (^{12}C, ^{12}N), (^{14}N, ^{14}C), and (^{14}N, ^{14}O), in addition to many others. Of these, the only ones actually observed were the (^{12}C, ^{12}B) and (^{14}N, ^{14}C) reactions, the cross sections of which varied from 2 to 8 mb. They also observed the (^{12}C, ^{11}B) and (^{14}N, ^{13}C) reactions with cross sections as high as 37 and 52 mb, respectively, and the (^{14}N, ^{12}C) reactions with a cross section of approximately 90 mb. The mechanism for the production of these reaction products could involve charge exchange between target and projectile followed by deexcitation of the projectile residue by evaporation of the appropriate number of nucleons.

It might be anticipated that these heavy ion induced (p, n) or (n, p) equivalent type reactions may exhibit an enhancement whenever transitions involving isobaric analog states of the target are possible. For example, the reactants and products of the ^{109}Ag(^{12}C, ^{12}B)^{109}Cd reaction described above have the following ground state isospins T: ^{109}Ag, $\frac{15}{2}$; ^{12}C, 0; ^{12}B, 1; and ^{109}Cd, $\frac{13}{2}$. ^{109}Cd should have a $T = \frac{15}{2}$ excited state which is the isospin analog of ^{109}Ag. In light of the well-documented[10] correlation between large cross sections and availability of such states, one would expect the ^{109}Cd production to be enhanced.

However, the transfer of a neutron to the heavy target and a proton to the projectile is hindered by the lack of an isobaric analog state ($T = \frac{15}{2}$) in the ^{109}Pd ($T = \frac{17}{2}$) product. Furthermore, when a $\Delta T = 0$ transition is possible between target nucleus and heavy product, it is not simultaneously possible between projectile and the light product. Therefore, light product breakup should be anticipated.

These data have been the stimulus for the experiments which have been undertaken in order to

examine reactions of the type described above. A target was selected which allowed examination of both the reaction in which the neutron is transferred to the projectile and the proton is transferred to the target [a (p,n) type reaction] and the opposite reaction in which the neutron is transferred to the target and a proton to the projectile [an (n,p) type reaction]. The target used was ^{65}Cu so that the (p,n) product was 245 day ^{65}Zn and the (n,p) product was 2.56 h ^{65}Ni. Excitation functions and average ranges for the reactions with both ^{11}B and ^{12}C projectiles were measured, as well as the ^{65}Zn angular distribution initiated with 88.6 MeV ^{12}C ions.

EXPERIMENTAL

Enriched ^{65}Cu (purchased from Oak Ridge National Laboratory) was fabricated into targets by electrodeposition.[11] These self-supporting targets were then irradiated in a stacked foil configuration in the Yale heavy ion linear accelerator. The target thicknesses 2–7 mg/cm^2 were chosen to enable simultaneous measurement of cross sections and thick-target thick-catcher average ranges. High purity aluminum (99.99%) was used for the recoil catcher foils. The beam energy was adjusted by placing high purity aluminum degrader foils between targets and the average energy in each target was determined with the aid of the tables of Northcliffe and Schilling.[12] The beam energy uncertainty was about ±2% except at the lowest energies where it was about ±5%. In addition, beam range straggling can introduce further uncertainties at low energies. After irradiation the samples were immediately counted several times on a high resolution Ge(Li) detector system. No radiochemical separations were performed on either targets or catchers. The samples were then allowed to decay for several weeks before again being counted to determine the ^{65}Zn activity.

The angular distribution was measured by means of an apparatus described in more detail elsewhere.[13] It consists of a flat catcher foil mounted perpendicular to the beam which is cut into concentric rings after irradiation. Each ring defines a fixed spread in recoil angles with respect to the target. The target used for this purpose was a thin 290 μg/cm^2 ^{65}Cu foil prepared by electrodeposition[11] on a backing of approximately 0.08 mm thick carbon sheet (obtained from Poco Graphite, Inc., Decatur, Texas).

RESULTS

Cross sections, corrected for recoil loss, were calculated from the measured γ activity and corrected for contribution from decay of the parent of the product. This correction was made by measurement of the γ decay rate of the ^{65}Ga parent. In all cases this correction was less than 10%. The average projected range R in the target material was determined from $R = FW$ where F is the fraction of the activity recoiling forward out of the target and W is the target thickness. The uncertainty associated with each cross section and average range was determined in the standard manner using the uncertainties in flux measurement, target thickness, detector efficiency, photopeak intensity, and irradiation time. In addition, an uncertainty of up to 5% in the range measurements could result from a possible copper impurity of <0.01% in the catcher foils. The results of these calculations may be seen in Table I and the

TABLE I. ^{65}Cu (HI, X)^{65}Zn.

Beam	Energy (MeV)	Cross section (mb)	^{65}Zn range (mg/cm^2 Cu)	Kinetic energy [a] (MeV)
^{12}C	122.0	218.5 ± 10.9	1.7 ± 0.1	10.2 ± 0.8
^{12}C	107.8	155.4 ± 5.6	1.2 ± 0.1	6.1 ± 1.0
^{12}C	99.1	79.4 ± 10.8	1.3 ± 0.2	6.8 ± 1.5
^{12}C	94.2	46.9 ± 3.7	0.9 ± 0.1	4.2 ± 0.6
^{12}C	88.8	33.1 ± 1.8	0.6 ± 0.1	2.6 ± 0.5
^{12}C	65.0	2.1 ± 0.4	0.3 ± 0.2	1.2 ± 0.5
^{12}C	43.6	0.8 ± 0.2	0.9 ± 0.3	4.2 ± 1.7
^{11}B	114.6	185.0 ± 10.4	1.3 ± 0.1	6.8 ± 0.8
^{11}B	107.2	200.2 ± 5.2	1.0 ± 0.1	4.9 ± 0.6
^{11}B	99.3	138.3 ± 9.3	1.4 ± 0.2	7.6 ± 1.5
^{11}B	72.9	68.0 ± 4.1	0.9 ± 0.2	4.2 ± 1.2
^{11}B	60.6	6.7 ± 0.7	1.0 ± 0.3	4.9 ± 1.1

[a] Determined from the range data by means of Northcliffe's tables, Ref. 12.

excitation functions for the production of ^{65}Zn are plotted in Fig. 1. The experimental differential cross section $d\sigma/d\theta$ for the production of ^{65}Zn from ^{65}Cu with 88.6 MeV incident ^{12}C ions is plotted in Fig. 2 versus laboratory angle θ. This quantity is proportional to the measured ^{65}Zn recoil activity observed in the annular ring. The ^{65}Ni activity could not be positively identified above background in any of the experiments and therefore an upper limit of 100 μb is estimated for its cross section.

DISCUSSION

There are a number of mechanisms which can be postulated for the reactions described above. Specifically, one can consider: (i) the complete fusion compound nucleus mechanism (CFCN); (ii) the simultaneous tranfer of a proton or neutron from target to projectile and the transfer of a neutron or proton, respectively, from projectile to target. This might be referred to as double nucleon switching to make a clear distinction from double transfer which normally refers to the transfer of two nucleons from one to the other of the reacting nuclei. This process of double nucleon switching can be considered analogous to charge exchange. The experimental results reported here do not provide any simple means of distinguishing between a charge exchange mechanism and one involving neutron-proton switching. (iii) Variations of nucleon switching or charge exchange in that one or both of the products may be left with sufficient excitation energy to result in subsequent nucleon evaporation. For the reactions under study this possibility is restricted to the unidentified light product. Thus, in the production of ^{65}Zn from ^{65}Cu with ^{12}C ions, considerable ^{12}B breakup could occur producing ^{11}B + n or ^{10}B + 2n, etc.

Mechanism (i), the CFCN mechanism, is least likely to contribute to the cross section at the incident energies employed in this experiment. The shape of the excitation functions shown in Fig. 1 is not typical of reactions taking place by the CFCN mechanism. Normally such reactions exhibit maxima in this range of excitation energy. A more convincing argument, however, is based on the results of a Monte Carlo evaporation calculation modeled after the work of Dostrovsky, Fraenkel, and Friedlander[14] which takes into account the evaporation of neutrons, protons, deuterons, tritons, ^{3}He, and α particles from nuclei at various excitation energies. The probability for the production of ^{65}Zn from the fused target-projectile system (^{65}Cu + ^{12}C = ^{77}Br*) was calculated at excitation energies of 70, 78, 86, 98, and 120 MeV. Five hundred evaporation calculations were performed at each energy. In no case was ^{65}Zn produced resulting from successive nucleon or particle evaporation. In fact no $A = 65$ mass products were observed from these calculations at any except the highest excitation energies, and then only in low yields of less than one mb. Thus, the CFCN mechanism cannot contribute in a major way to the observed cross section. Also, the absence of a measured yield for ^{65}Ni implies that

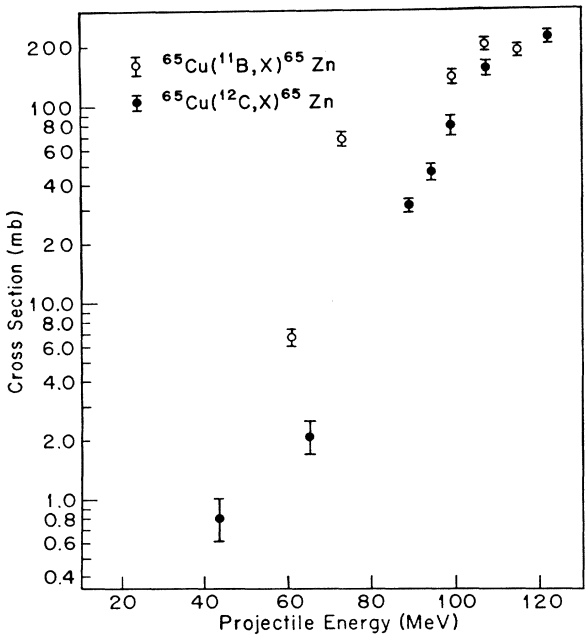

FIG. 1. Excitation functions for the production of ^{65}Zn from ^{65}Cu with ^{11}B and ^{12}C projectiles.

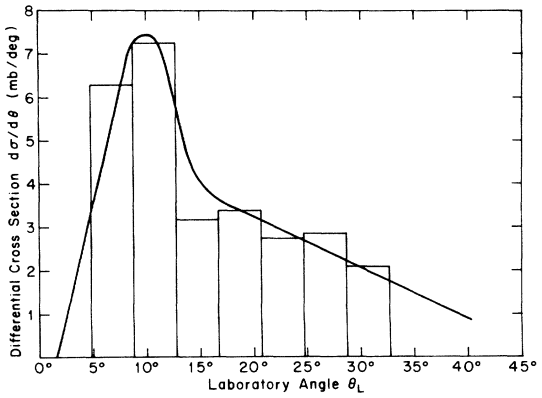

FIG. 2. Angular distribution of the ^{65}Cu(^{12}C, X)^{65}Zn reaction at 88.6 MeV incident ^{12}C kinetic energy. The smooth line represents a Gaussian form with an arbitrary tail fitted by a least squares procedure.

contributions from an incomplete compound nucleus mechanism must be of low probability.

The angular distribution, illustrated in Fig. 2 for the production of ^{65}Zn from ^{65}Cu with 88.6 MeV incident ^{12}C ions, indicates a peaking at 10–12° in the laboratory with a broad distribution of lower intensity extending to higher angles. The low angle peak is similar to that observed for other nucleon transfer reactions.[8,9,15] The distribution of ^{65}Zn nuclei at larger angles might result from a second mechanism. However, at least part of the large angle differential cross section might be caused by large angle scattering of the ^{65}Zn, essentially the same mass as ^{65}Cu, in the copper target which had a mass of about half the average range.

The ^{65}Zn recoil ranges, converted to recoil kinetic energies by means of Northcliffe's tables,[12] are illustrated in Fig. 3. The solid line represents the product kinetic energies predicted on the basis of a complete momentum transfer from the projectile to a fused projectile-target system and further assumes that all subsequent nuclear evaporation is isotropic in the moving fused (compound nucleus) system. The experimentally observed ^{65}Zn kinetic energies are considerably below these predicted values.

Product recoil kinetic energies based on double nucleon switching can be estimated from the quasielastic model of Strudler *et al.*[7] According to this treatment the nuclear interaction is divided into two parts which are assumed to be independent. First a portion of the projectile is completely absorbed by the target and this resulting fused system receives a momentum in the forward direction corresponding to the fraction of the projectile momentum represented by the absorbed part of the projectile. The remainder of the projectile is then assumed to undergo elastic scattering with the newly formed reaction intermediate.

The open triangles indicated in Fig. 3 represent the results of a calculation based on this model for the case of neutron-proton switching. The expected inverse dependence of energy transfer versus incident energy is observed. Calculations based on this model[16] indicate that as more of the mass of the projectile is transferred to the target the energy transfer changes gradually from the inverse dependence with incident energy observed for elastic scattering to the nearly linear dependence observed for the compound nucleus mechanism. Clearly this model, in this simple form, does not fit the data except for perhaps the two points at 44 and 65 MeV.

The data can be compared to quasielastic Rutherford scattering according to which the kinetic energy transferred to the struck particle is given by:

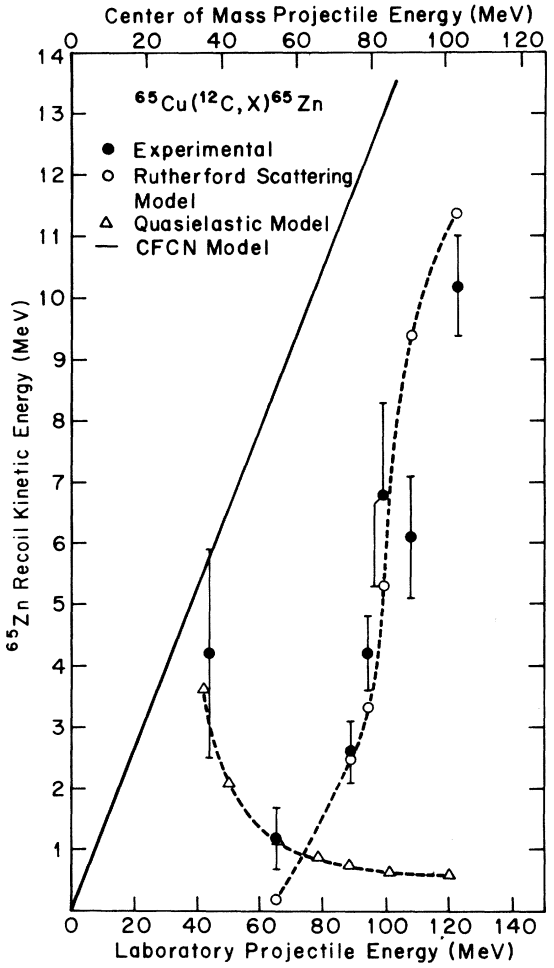

FIG. 3. ^{65}Zn recoil energy versus projectile kinetic energy for the ^{65}Cu(^{12}C, X)^{65}Zn reaction. The recoil kinetic energies were obtained by conversion of the experimental range data. Also indicated for comparison are the predicted values of the ^{65}Zn kinetic energy based on the CFCN mechanism, the quasielastic model, and Rutherford scattering.

$$E_T = \left(\frac{M_1}{M_2}\right)\frac{E_C^2}{E_i},$$

where M_1 and M_2 are the masses of the projectile and target nucleus, respectively, E_C the Coulomb energy given by $Z_1Z_2e^2/d$, and d is the distance of closest approach. In the application presented here the distance d includes the collision diameter and the incident energy E_i is corrected by the reaction Q value. For the reaction ^{12}C + ^{65}Cu = ^{12}B + ^{65}Zn the Q value is −14.72 MeV. The Q value for the same reactants leading to a neutron, ^{11}B and ^{65}Zn is −18.08 MeV.

Values of the distance of closest approach d, for the $^{12}C + ^{65}Cu$ reaction, were obtained using the experimentally determined ^{65}Zn recoil kinetic energies, after smoothing, and are listed in Table II. It is interesting to note that the quantity $d^2\sigma$ is nearly constant for all incident energies above 65 MeV, implying that the interaction is inversely proportional to the square of the closest distance of approach. The curve indicated by open circles in Fig. 3 represents a fit of the data based on the best average value for the proportionality constant given by $\sigma = kd^{-2}$. Values of the calculated recoil kinetic energies are also listed in Table II.

This relationship between cross section and interaction or collision distance is suggestive of the kind of behavior one would expect based on a charge-exchange or double nucleon switching mechanism.

The ^{65}Zn angular distribution measured for 88.6 MeV ^{12}C ions indicates a peaking at a laboratory angle of about 10°, similar to other types of grazing collisions. Assuming that the light fragment is ^{12}B, momentum balance requires one to predict that the angular distribution for ^{12}B would peak at about 7°. Similar angles have been observed for other types of transfer reactions.[9] The rather broad distribution observed for the ^{65}Zn angular distribution may be related to the high probability of ^{12}B breakup into $^{11}B + n$, $^{10}B + 2n$, etc.

The failure to observe any yield of ^{65}Ni, while the cross section for ^{65}Zn is over 200 mb, is consistent with the suggestion that population of the isobaric analog of the target ground state is enhanced. The ground state isopin of ^{65}Cu is $T = \frac{7}{2}$, that of ^{65}Ni is $\frac{9}{2}$, and for ^{65}Zn it is $T = \frac{5}{2}$. Hence, the appropriate isobaric analog state of ^{65}Cu is not available in ^{65}Ni but is present in ^{65}Zn. Although the evidence provided by this example does not permit a general conclusion, the enhancement of $\Delta T = 0$ transitions supports charge exchange or the p-n switching mechanism.

TABLE II. Calculated recoil kinetic energies and distances of closest approach for the $^{65}Cu(^{12}C, X)^{65}Zn$ reaction.

Incident energy (MeV)	Distance of closest approach d (fm)	σd^2 (b fm^2)	Recoil kinetic energy (MeV)
122.0	3.24	2.29	11.4
107.8	3.72	2.15	9.4
99.1	5.00	1.99	5.3
94.2	6.45	1.95	3.3
88.8	7.76	1.99	2.5
65.0	31.40	2.07	0.2
43.6	...	...	...

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