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RECOIL RANGES OF PRODUCTS FROM REACTIONS OF Cu^{65} WITH 11-33 MeV He^3 IONS*

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Hard copy (HC) $1.00

Microfiche (MF) .50

#653 July 65

by

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Abstract

Average projected ranges have been determined for the (He^3,n), $(He^3,2n)$, and (He^3,α) reactions of Cu^{65} over the energy range of 11-33 MeV. The results have been compared with calculations based on the assumption of compound nucleus formation. Excellent agreement is obtained for the $(He^3,2n)$ reaction at all energies and for the (He^3,n) reaction up to 17 MeV. The ranges of Cu^{64} are much smaller than the theoretical values at all energies indicating that the (He^3,α) reaction involves a direct interaction.

* Supported by the U. S. Atomic Energy Commission.

† Supported in part by NASA.

FACILITY FORM 602

N66 31374 (ACCESSION NUMBER) (THRU)

14 (PAGES) 1 (CODE)

CR-76396 (NASA CR OR TMX OR AD NUMBER) 24 (CATEGORY)

I. Introduction

In a recent report[1] we presented the results of a recoil study of several reactions of Cu^{65} with medium-energy He^4 ions. This study consisted of a determination of the average projected ranges of the product nuclei. The recoil ranges are directly related to the momentum transferred to the struck nucleus by the incident particle. The momentum transfer is, in turn, a sensitive probe of the reaction mechanism. In the case of a compound nuclear process the projectile thus transfers its entire momentum to the compound nucleus. The subsequent evaporation of particles is symmetric about 90° in the center-of-mass system and has a relatively minor effect on the recoil range. On the other hand, in a direct interaction the momentum brought in by the projectile is to a large extent immediately removed by the predominantly forward emission of particles. The recoil range of the product will therefore be considerably smaller than in the case of compound nucleus formation.

In our earlier work[1] we found that the ranges of the (α,n), $(\alpha,2n)$, and $(\alpha,3n)$ reaction products indicated the predominant occurrence of compound nucleus formation at all energies studied, i.e. up to 43 MeV. On the other hand, the ranges of Cu^{64} indicated a sizeable contribution of a direct process to the $(\alpha,\alpha n)$ reaction above 30 MeV.

The present work concerns a similar study of the reactions of Cu^{65} with He^3 ions. Comparison with the He^4 recoil studies should indicate the relative importance of direct and compound nuclear mechanisms for these two projectiles. We report results for the (He^3,n), $(He^3,2n)$, and (He^3,α) reactions for incident energies of 11-33 MeV. The excitation

functions of some of these reactions have previously been determined by Bryant et al.[2] These authors obtained qualitative agreement with statistical model calculations. Recoil measurements are more sensitive to direct interaction admixtures and the present work shows a significant contribution of this process to some of the above reactions.

II. Experimental Procedure and Results

The experimental procedures are similar to those given in our previous report[1] and only a brief summary will be given here. The targets consisted in most cases of self-supporting foils of highly enriched copper-65[3], 4-6 mg/cm^2 in thickness. In some instances foils of natural isotopic composition (1.8 mg/cm^2 thick) were also employed. The forward catcher foils consisted of 0.001 inch thick aluminum foils of high purity (99.999%). It was previously established that the contribution to the observed activity of impurities in the aluminum was negligible. The target stacks usually consisted of 5 to 10 target and catcher foils together with appropriate degrader foils. A range energy relation based on that of Bichsel et al[4] for protons was used to determine the bombarding energy at any given position in the stack.

Irradiations were performed with the He^3-ion beam of the 60-inch cyclotron at Argonne National Laboratory. The irradiation conditions were similar to those described previously.[1] After bombardment copper and gallium were radiochemically separated from the various samples. The activity measurements were performed with scintillation and γ-γ coincidence spectrometers.

The present type of experiment permits the determination of the projection along the beam direction of the average range of the product in the target material. This quantity is given as

$$R_p = FW \qquad (1)$$

where F is the fraction of the total activity of the product found in the forward catcher foil and W is the target thickness. It is here assumed that all of the recoiling products are emitted at an angle of less than 90° with respect to the beam direction. The kinetmatics of low-energy reactions in most cases insure that this condition is met. Eq. (1) also assumes that the formation cross section for the nuclide of interest is constant throughout the target. This is often not the case for reactions having steep excitation functions and corrections for this effect were first considered by Porile.[5,6] In the present study this correction amounted to less than 3 percent and was neglected.

Average projected ranges for the (He^3,n), (He^3,2n), and (He^3,α) reactions have been measured over the energy range of 11-33 MeV. The results are summarized in Table I and plotted as a function of bombarding energy in Figure 1. The estimated experimental error of 15-20 percent includes the uncertainties in the disintegration rate and chemical yield determinations as well as the effect of non-uniformity in the target thickness. The scatter of the experimental points is consistent with this estimate.

The ranges of the various reaction products are seen to exhibit differing trends with bombarding energy. In the case of the (He^3,2n) reaction the ranges increase monotonically with energy indicating an

increasing momentum transfer to the struck nucleus. The ranges of Ga^{67}, formed in the (He^3,n) reaction, approach a constant value at an incident energy of about 17 MeV. Evidently a direct process contributes to the reaction at the higher energies.

The ranges of Cu^{64} have a rather complicated energy dependence. In order to obtain further information about this reaction its excitation function was measured. The results are shown in Figure 2. The breadth of the curve and the possible occurrence of a minimum suggest a contribution from different reaction paths. At low energies we expect the (He^3,α) reaction, whose Q-value is positive, to be the principal contributor to the formation of Cu^{64}. The Q-values of the (He^3,He^3n) and $(He^3,2p2n)$ reactions are -9.9 and -17.6 MeV respectively. One or both of these reactions appear to make a significant contribution to the Cu^{64} formation cross section at the higher energies.

III. Discussion

The measured recoil ranges may be compared with a calculation based on the assumption of compound nucleus formation. We follow the approach used in our previous work.[1] The momentum of the compound nucleus is modified by the evaporation of particles. This effect is determined by an adaptation[7,8] of the Monte Carlo evaporation code by Dostrovsky et al.[9] At the end of the evaporation chain the product nucleus has a certain kinetic energy and is moving in a particular direction with respect to the beam. The use of the range-energy relation of Lindhard et al[10] permits the conversion of kinetic energy to recoil range and projection of the latter along the beam axis gives the value of R_p.

One thousand iterations were performed at a given bombarding energy and the resulting R_p values for each product were averaged for comparison with experiment. As in our previous calculation, the level density parameter was chosen as $\underline{a} = A/20$ and the nuclear radius parameter as $r_o = 1.5f$.

The results of the calculation are given by the solid lines in Figure 1. Excellent agreement with experiment is obtained for Ga^{66}, produced by the $(He^3,2n)$ reaction. The excitation function for this reaction[2] peaks at a bombarding energy of about 16 MeV. Evidently, a compound nuclear process remains the dominant mechanism for this reaction at least 16 MeV beyond the peak energy. A similar conclusion was reached by Hazan and Blann[11] in the case of the $Fe^{56}(He^3,2n)$ reaction.

The calculated ranges for Ga^{67} are in very good agreement with the experimental values up to a bombarding energy of 17 MeV but are significantly larger than the latter above this energy. A look at the excitation function for the (He^3,n) reaction[2] indicates that this discrepancy sets in only 4 MeV beyond the peak energy. By contrast, the recoil ranges for the $Cu^{65}(\alpha,n)$ reaction[1] remain in agreement with the compound nucleus calculation for at least 18 MeV beyond the corresponding peak energy. This difference between the two projectiles is suggestive of a stripping mechanism for the (He^3,n) reaction at the higher energies. The more tightly bound alpha particle is obviously much less susceptible to stripping. The experimental results above 17 MeV are consistent with an average neutron emission angle of approximately 55 degrees on the assumption that the residual nucleus is left in a low-lying state. This value appears to be somewhat larger than expected for a pure stripping process and may indicate an admixture of a compound nuclear mechanism even at the higher energies.

The theoretical range curve for Cu^{64} predicts much larger values than are obtained experimentally. The decrease in the calculated ranges observed at about 23 MeV is due to the change from a (He^3,α) to a $(He^3,2p2n)$ reaction. This is clearly seen in Figure 2 where the calculated excitation function shows two branches ascribable to the above reactions. This change in mechanism leads to a decrease in the predicted range both because of the inherently larger recoil associated with the emission of a single heavy particle as opposed to four light particles and of the sudden decrease in the kinetic energy of the evaporated particles.

The decrease in the experimental ranges from values that approach the calculated ones at low energies reveals an increasing contribution of a direct process, presumably pickup, to the (He^3,α) reaction. A calculation of the range expected according to this mechanism reveals, in fact, that recoil should occur in the backward direction. Confirmatory angular distribution measurements of the Cu^{64} recoils are currently in progress.[12] The increase in the measured recoil ranges observed above approximately 28 MeV implies an increasing momentum transfer to the struck nucleus. It is reasonable to attribute this increase to the $(He^3,2p2n)$ reaction, as is also suggested by the measured excitation function. The fact that the ranges remain much smaller than the values expected for compound nucleus formation probably indicates that there is still a significant contribution from the (He^3,α) reaction at the highest energies studied.

The cooperation of Mr. M. Oselka and the crew of the Argonne 60-inch cyclotron is appreciated.

Table I

Experimental Average Projected Ranges

Bombarding Energy (MeV)	R_p (mg/cm^2)		
	Ga^{67}	Ga^{66}	Cu^{64}
32.6	.150*	.237*	.122*
30.8	.196	.253	
28.5	.149*	.227*	.069*
25.5	.130*	.204*	.052*
25.3	.168	.250	
22.3	.142*	.191*	.049*
20.0	.142	.183	
18.2	.140*	.174*	.050*
17.3	.151*	.145*	
16.2	.118*	.123*	.093*
14.5	.130	.121	.138
14.0	.119*	.123*	.159*
11.3	.046	.029	.087

* Enriched Cu^{65} target.

Figures

Figure 1 - Energy dependence of the average projected ranges. The solid curves are the result of a calculation assuming compound nucleus formation.

Figure 2 - Excitation function of the (He^3,α) reaction. The solid curve is drawn through the experimental points. The dashed curve is the result of a statistical theory calculation.

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