2π-Differential Recoil Study of the $Cu^{65}(p,pn)Cu^{64}$ Reaction*

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The 2π-differential recoil range of the $Cu^{65}(p,pn)Cu^{64}$ reaction has been determined with incident protons of 130 and 396 MeV. The number of Cu^{64} atoms which recoiled from copper targets about 10 $\mu g/cm^2$ thick and caught in aluminum absorbers of varying thickness from about 10 $\mu g/cm^2$ to about 180 $\mu g/cm^2$ were determined. The resulting integral recoil distribution at 396 MeV indicate that there are two groups of recoiling Cu^{64} nuclei. The short-range group has a maximum range of about (45 ± 5) $\mu g/cm^2$ of aluminum, and the long-range group has a maximum range of about (180 ± 8) $\mu g/cm^2$ of aluminum. At 130 MeV only one recoil range was observed, which has a maximum range of about (50 ± 5) $\mu g/cm^2$ of aluminum. The angular distribution of the recoiling Cu^{64} nuclei was also determined using a 10-$\mu g/cm^2$ copper target and thick aluminum catcher foils. The short-range Cu^{64} recoils were interpreted in terms of an inelastic (p,p') scattering mechanism followed by neutron evaporation. The long-range recoils can be interpreted in terms of the knock-out mechanism. The relative number of events taking place by these two mechanisms is about equal. Reasonable agreement is obtained between predictions based on the two mechanisms and the experimental observations.

INTRODUCTION

IN the preceding paper[1] the main experimental features that have been observed from studies of the product recoil behavior of (p,2 nucleon) reactions were described. In view of the extreme difficulty in properly interpreting the experimental results of studies involving the measurement of the number of product recoil atoms produced from targets of thickness larger than the recoil range, a differential recoil range determination was undertaken. The experiments described here allow a direct measurement of the recoil range of the product nucleus in the particular target system employed, and have the very important advantage that they do not require the postulation of velocity vector diagrams for interpretation of the experimental results. On the other hand, these experiments do suffer from the disadvantage that the number of product recoils was measured in an absorber which subtended an angle of 2π steradians. This results in averaging problems in which the experimentally determined range is actually a weighted average depending on the particular angular distribution. It is difficult to assess the seriousness of this problem and the effect it plays in the interpretation of the data presented. However, until it becomes experimentally possible to measure the differential recoil range and angular distributions simultaneously, the experiments reported here provide many fewer uncertainties than the conventional thick-target, thick-catcher experiments described in the preceding paper, and at the same time, the results from these new experiments provide greater insight into the nature of these reactions.

The $Cu^{65}(p,pn)Cu^{64}$ reaction was chosen to be studied in this work since: (1) the thick-target, thick-catcher experiments had already been reported for this reaction up to[2] 400 MeV, (2) these latter experiments showed an interesting energy dependence of the effective recoil ranges not found in any similar study reported to date[1,3] and (3) experimental range energy relations exist for ions of mass 65–70.[4] As an aid in the interpretation of the results of these 2π-differential measurements, the angular distribution of Cu^{64} from the $Cu^{65}(p,pn)Cu^{64}$ reaction was also determined using thin targets and thick catchers.

EXPERIMENTAL PROCEDURES

All bombardments were made in the circulating beam of the Carnegie Institute of Technology synchrocyclotron. The energies were selected by placing the targets at different radial positions in the cyclotron. A typical target packet is shown in Fig. 1. For the target, a "monolayer" of copper nuclei was approached by evaporating $\sim$10 $\mu g/cm^2$ of high purity, 99.999%, copper upon 99.999% pure 2-mil aluminum foils. Adjacent to this target was placed a catcher foil. The catcher foil consisted of a variable amount (from 9 $\mu g/cm^2$ to 255 $\mu g/cm^2$) of 99.999% pure aluminum evaporated upon 99.99% pure 3-mil iron foils. The weights of both copper targets and aluminum absorbers were obtained, respectively, by weighing by difference several times the original backing foil and the foil plus evaporated metal on a Mettler Micro-balance where a weight could be obtained within an accuracy of ±1 $\mu g/cm^2$. Since a series of bombardments of varying aluminum catcher thicknesses had to be made to

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[1] D. L. Morrison and A. A. Caretto, Jr., preceding paper, Phys. Rev. 133, B1165 (1964).

[2] E. R. Merz and A. A. Caretto, Jr., Phys. Rev. 126, 1173 (1962).

[3] S. Singh and J. M. Alexander, Phys. Rev. 128, 711 (1962).

[4] N. Porile (unpublished data).

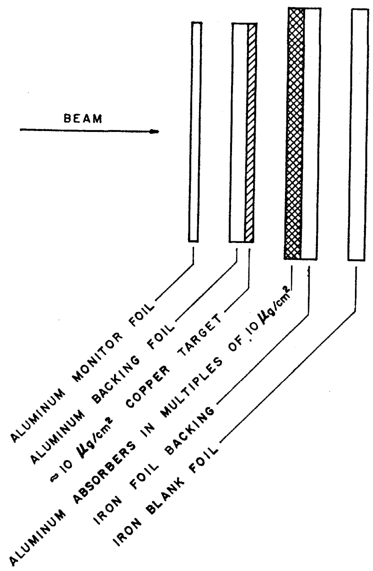

FIG. 1. Schematic representation of target packets used in the 2π-differential recoil study (not to scale).

determine the range distributions of recoiling product nuclei, aluminum foils were included in the packets to monitor the proton beam intensity. Finally at the end of each packet was placed another piece of 3-mil iron foil used as a blank to determine the Cu^{64} activity produced in the iron from nuclear reactions on impurities in the iron. When the aluminum absorber segments of the catcher foils were thick enough to absorb all the Cu^{64} nuclei recoiling from the copper target, the Cu^{64} activity of the iron backing of the catcher foil became equal to that of the iron blank foil, and the maximum range of the Cu^{64} recoils could be determined. The copper targets with aluminum backings and the aluminum monitors were obtained from the foils with a square punch, 0.50 by 0.50 in., so as to insure reproducible areas. The catcher foils and blank foils were cut to a slightly larger area.

Each target packet was irradiated for 15 min at one-half the normal beam intensity. Following the bombardments the aluminum catchers were chemically removed from the iron backings by treatment with alkali, and the Cu^{64} activities were separated from these aluminum catchers, from the iron backings and from the iron blank foils using the radiochemical procedure described by Merz and Caretto.[2]

Contributions to the Cu^{64} activities found in the aluminum catchers, due to sources other than recoils from the copper target, were negligible because of the high purity of the materials used in the targets. This was verified in a determination made in which the target packet was kept unchanged with the exception that no copper was evaporated on the aluminum backing foil. In this experiment less than 3% of the Cu^{64} activity found in a normal comparable run was found in the aluminum absorber of the catcher.

The target assembly used in the integral angular distribution study is shown in Fig. 2. The target consisted of a strip about 1 mm wide of 2-mil aluminum upon which $\sim 10\ \mu g/cm^2$ of copper had been evaporated. This target was stretched down the center of a quarter cylinder 2 cm in diameter, with the copper facing towards the cylinder's leading edge. The inner surface of the quarter cylinder was lined with three aluminum foils which served as a catcher foil, a blank foil and a guard foil, respectively. The cylinder was made of aluminum so as not to contribute to the Cu^{64} activity. In one bombardment the integral angular distribution from 0 to 90° was obtained. By revolving the quarter cylinder 180°, the distribution from 90 to 180° could be obtained. Following bombardment, the catcher foil and the blank foil were cut into 3 segments corresponding to solid angles of 30 deg each. The Cu^{64} activity found in each of the blank segments was then subtracted from that in the appropriate catcher segment to give the Cu^{64} activity in the catcher segments due only to recoils from the target strip. The bombardment from 0 to 90° was normalized to that from 90 to 180° by means of the Cu^{64} activity found in the blank foil.

All copper samples were mounted on 2-in.-diam stainless steel planchets with double-sided Scotch tape and were covered with Saran wrap. They were counted in a commercial, low level, beta counter manufactured by Sharp Laboratories. The background of the detectors of this counter did not exceed 2 cpm during this study. Since all Cu^{64} activity measurements were relative to one another, only a self-absorption and scattering correction term had to be applied to them. However, due to the nearly constant chemical yields that were obtained in these experiments the variation in the value of these correction terms was generally negligible and therefore the correction could often be neglected. All activities were extrapolated back to the end of bombardment and were corrected for chemical yields.

Each individual bombardment, as well as each series of bombardments, had to be normalized to a common beam intensity and a common target thickness. The relative beam intensities were determined by comparison of the amount of Na^{22} produced in the standard size 2-mil aluminum monitor foils via the $Al^{27}(p,3p3n)$-

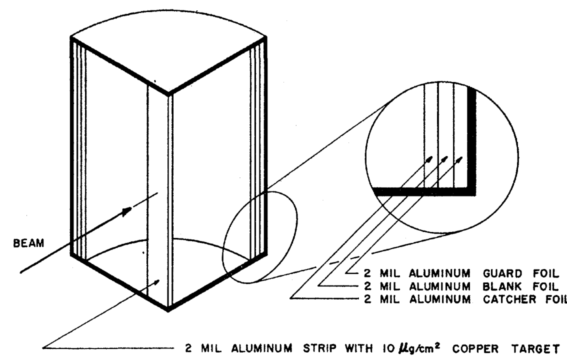

FIG. 2. Schematic representation of target assembly used in the integral angular distribution study.

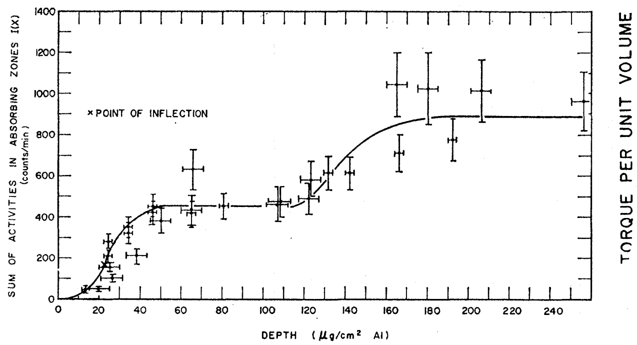

FIG. 3. Experimentally measured integral distribution of Cu^{64} nuclei in the forward direction at 396 MeV.

Na^{22} reaction. The radiations of the Na^{22} were detected with a beta-proportional counter. A target thickness of 10.0 $\mu g/cm^2$ of copper was chosen as the standard target thickness, and all data were normalized to this.

RESULTS

The experimental data obtained are Cu^{64} activities found in aluminum absorbers of thickness: Δx_1, $\sum_{i=1}^{i=2}\Delta x_i, \cdots \sum_{i=1}^{i=n}\Delta x_i$. These Cu^{64} activities were plotted versus depth at the maximum depth of the absorber, and are shown in Figs. 3, 4, and 5. Illustrated in Fig. 3 is the recoil distribution in the forward direction at 396 MeV, in Fig. 4 is the recoil distribution in the backward direction at the same energy, and Fig. 5 shows the recoil distribution in the forward direction at 130 MeV. These figures essentially represent integral distributions since each data point corresponds to Cu^{64} recoils stopped at any depth of absorber up to that point. These figures were drawn according to the following procedure. Making reference to Fig. 3, that portion of the data at thicknesses greater than $\sim$160 $\mu g/cm^2$ were connected with a straight line of zero slope. At some thickness, all energy recoils should be stopped and "integral" curves, such as shown here, should show a distribution parallel to the abscissa. This line was drawn by a least-squares fit of the data points. In a similar way, the line through the data points at thicknesses between $\sim 45\ \mu g/cm^2$ and $\sim 120\ \mu g/cm^2$ was drawn by a least-squares fit. The justification that this portion of the integral distribution also has a zero slope is based first on visual inspection of the data and second on a chi-squared test of the goodness of fit of the line drawn as illustrated. A confidence level between 60 and 90%, depending on how many points were used, was obtained for the step function shown in Fig. 3. A confidence level no larger than 10% was obtained if the best "smooth" curve was drawn through the data. The uncertainty in the points making up the integral curves shown in Fig. 3, 4, and 5 were generally taken to be about 15%. This uncertainty is made from the following contributions: 10% due to the beam intensity correction applied to each bombardment, 6% from the uncertainty in copper target thickness, 5% from decay curve resolutions and 5% from uncertainty in chemical yields. This gives a root square error of 13.6%. The horizontal uncertainty shown in the thicknesses of the absorbers was taken to be the maximum displacement obtained in any series of weighings, $\sim 5\ \mu g/cm^2$. It is felt that the variation in the weights of all the catcher foils is due mainly to oxidation of the iron backing and not to change in weight of the aluminum absorber. If this is the case, the horizontal uncertainties can be reduced to about 1–2 $\mu g/cm^2$ per aluminum film.

Uncertainties due to range straggling are large, particularly for ranges less than about 60 $\mu g/cm^2$ of aluminum. The magnitude of this effect was estimated, using the formalism of Lindhard and Scharff,[5] and amounts to about 30% of the projected range for all ranges up to about 60 $\mu g/cm^2$. At ranges above this value, the straggling effect should be considerably lower since this corresponds to the scattering region where energy loss to electrons becomes dominant.

In the scattering region less than about 60 $\mu g/cm^2$, where the equations of Lindhard and Scharff are valid, it is interesting to note that substantially the same energies are predicted as were experimentally determined by Porile,[4] within the experimental uncertainties.

Error assignment to the angular distribution study is considerably more obscure. In addition to the conventional uncertainties because of beam intensity corrections, target thickness nonuniformity, chemical yield determinations and decay curve resolutions, this study contained an inherent uncertainty the value of which is hard to estimate. This uncertainty was due to the bending of the recoiling Cu^{64} nuclei as they traversed the distance from the target to the catcher foil, $\sim$2 cm, by the magnetic field of the cyclotron. Since the charge on these recoils was not known, any estimate of

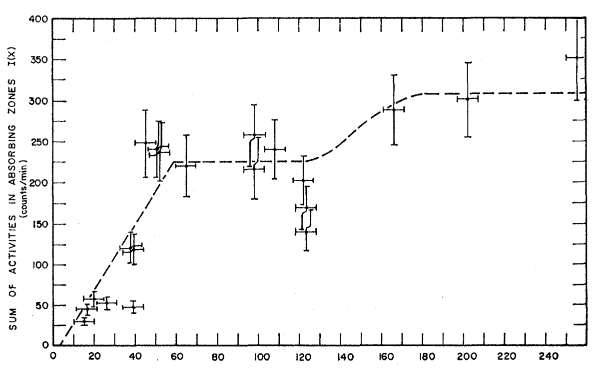

FIG. 4. Experimentally measured integral distribution of Cu^{64} nuclei in the backward direction at 396 MeV.

[5] J. Lindhard and M. Scharff, Phys. Rev. **124**, 128 (1961).

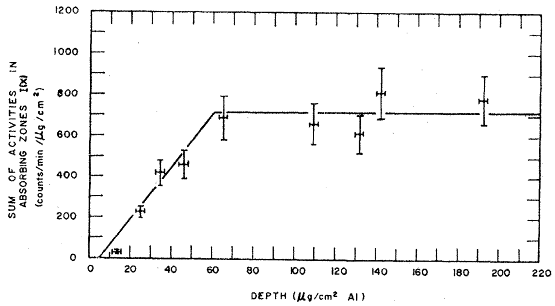

FIG. 5. Experimentally measured integral distribution of Cu^{64} nuclei in the forward direction at 130 MeV.

this uncertainty would be speculation. For this reason no uncertainty was placed on the results of this study, and the error flags shown in Fig. 6 are merely indicative of the reproducibility of the two runs made.

DISCUSSION

The most interesting feature observed from these experiments is the step distribution of the range data at 400 MeV. Due to the complexity of the interaction involved in (p,2 nucleon) reactions, the nature of the momentum transfer to the product recoil is particularly difficult to interpret as was mentioned previously by Morrison and Caretto.[1] Thus it is not very easy to present a unique interpretation of these data. Considerably more experimental investigations must be undertaken before an unambiguous interpretation of recoil behavior can be made in terms of the various factors entering into a (p,2 nucleon) nuclear interaction. Despite the absence of the proper quantal calculations which would provide a guide for interpretation of reactions of this type, it is of interest to speculate how various reaction mechanisms might predict the observed experimental behavior. Interpretations in this manner are useful as a guide toward the planning of future experiments.

Differentiation of the curves presented in Figs. 3 and 4 would yield curves characterized by two peaks, one extending from about zero to 50 μg/cm² of aluminum and another extending from about 120 to 180 μg/cm² of aluminum. Since the relevant data are obtainable directly from the integral distributions presented in Figs. 3 and 4, and since the differential curves corresponding to the integral distributions would have very large uncertainties associated with them, due to the multiple subtractions involved, such differential distributions are not presented.

Short-Range Distribution

The short-range distribution corresponds to a Cu^{64} nucleus with a maximum range of about (45±5) μg/cm². Using the experimental range-energy relation determined by Porile[4] this corresponds to a kinetic energy of about (140±56) keV. The most probable recoil range occurs at the point of inflection of the curve, and is at $\sim$22 μg/cm². This corresponds to a Cu^{64} with a most probable recoil kinetic energy of about (70±20) keV.

The shape of the short-range distribution curve and the Cu^{64} kinetic energy, to which it corresponds, is indicative of the results that might be expected from the ISE mechanism. (See previous paper.) The forward momentum imparted to the Cu^{65} nucleus as a result of a (p,p') interaction is quite trivial (about 5 keV assuming zero angle scattering and 20 MeV of residual excitation energy). Since the binding energy of a neutron in Cu^{65} is 9.9 MeV, residual Cu^{65} nuclei from the (p,p') event with excitation energies between about 10 and 20 MeV will give rise to the Cu^{64} product by the evaporation of a neutron. Residual nuclei with excitation energies in excess of 20 MeV can also evaporate neutrons to produce Cu^{64}, but in this case competition via multiple evaporation paths, now energetically favorable, will take precedence over single neutron evaporation. Since the distribution of the number of residual Cu^{65} nuclei after (p,p') events is peaked at an excitation energy of about 25 MeV,[6] the Cu^{64} recoil momenta, resulting from single neutron evaporations from this spectrum of excited Cu^{65} nuclei, should be similarly peaked about some value dependent on the most probable evaporated neutron kinetic energy. In Fig. 7 is illustrated the relative neutron evaporation probabilities for Cu^{65} nuclei with 20, 30, and 40 MeV of excitation energy, and an average neutron evaporation probability curve weighted by the probability distribution of having Cu^{65} residual nuclei with any excitation energy in this range (see Ref. 6). The most probable neutron kinetic energy, corresponding to the weighted average spectrum illustrated in Fig. 7, is about 2.5 MeV. If the Cu^{64} recoil kinetic energy corresponding to the point of inflection in the range curve is inter-

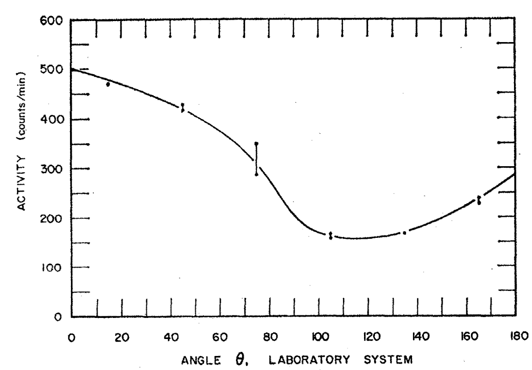

FIG. 6. Experimentally measured angular distribution of Cu^{64} nuclei (angle θ is in the laboratory system).

[6] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 185 (1958).

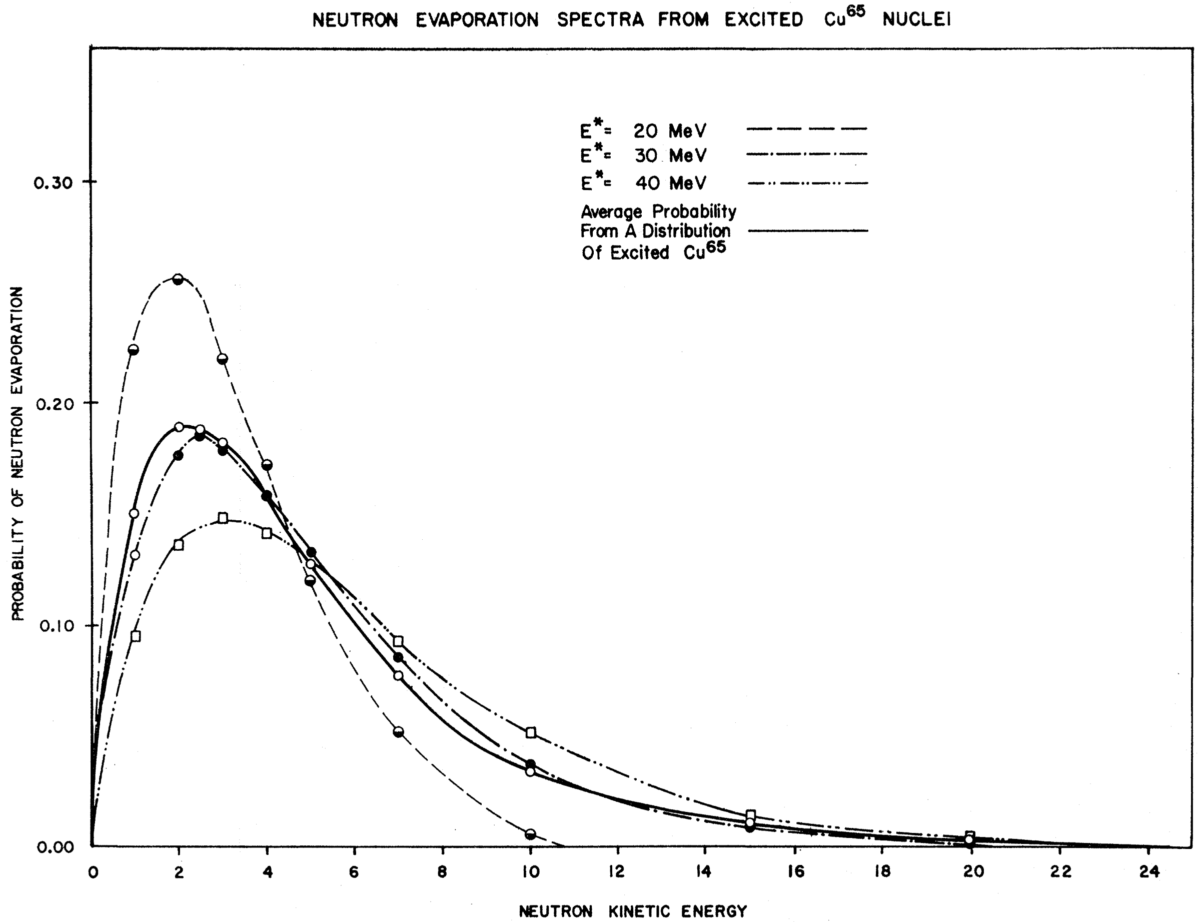

FIG. 7. Relative neutron evaporation probabilities from excited Cu^{65} nuclei.

preted as arising from the evaporation of a neutron from an excited Cu^{65} nucleus, then the most probable neutron kinetic energy, corresponding to the data, is about (4.5±1.3) MeV. The agreement is reasonable considering the large uncertainties in both the experimental data and the range-energy data.

The integral range distribution, for 396-MeV incident protons, of Cu^{64} nuclei recoiling between 90° and 270° from the beam (the backward direction) is shown in Fig. 4. The uncertainties of these data are larger than for the foıward distribution because the activity in samples of corresponding aluminum absorber thicknesses are lower by about a factor of three in the backward distribution, and fewer determinations were made. However, the data exhibit a similar short-range distribution from about zero to about (50±5) $\mu g/cm^2$ of aluminum. Continuing with speculations as to reaction mechanism, the kinetic energy of a Cu^{64} nucleus recoiling in the backward direction should be the same as in the forward direction, as the data indicate, if the major portion of this energy comes from the evaporation of the neutron following a (p,p') event. Neutron evaporation will be isotropic in the system of the moving target nucleus and hence the backward low-range distribution should be identical to the forward with the exception of a small effect due to the initial (p,p') event. As mentioned previously, the (p,p') event can deposit a maximum of about 5-keV kinetic energy in Cu^{64}. In the absence of further experimental investigation of the short-range distribution it is only possible to conclude that this interpretation involving the ISE mechanism is consistent with the experimental observations.

Long-Range Distribution

The data in Fig. 3 indicates that a longer range distribution exists in which the most probable range is about (150±5) $\mu g/cm^2$ of aluminum and a maximum range of about (180±8) $\mu g/cm^2$ of aluminum. The Cu^{64} recoil kinetic energies corresponding to these ranges, and listed in Table I, are (530±106) keV and (670 ±130) keV, respectively. The expectation value of the recoil kinetic energy that might be expected from the abrupt removal of a neutron from the Cu^{65} nucleus, assuming a square potential well, is about 304 keV,

TABLE I. Cu^{64} recoil kinetic energies.

	Short range maximum kinetic energy (keV)	Long range most probable kinetic energy (keV)	Long range maximum kinetic energy (keV)
396 MeV forward direction	140±56	530±106	670± 30
396 MeV backward direction	145±56	510±100	670±150
130 MeV forward direction	150±60	···	···

whereas the "maximum" recoil kinetic energy arising from the removal of a neutron from the top level of a square nuclear well, 35 MeV deep,[7] is 550 keV. This expectation value, of 304-keV recoil kinetic energy, corresponds to the average neutron kinetic energy in Cu^{65} assuming a degenerate neutron Fermi gas contained in a square well potential. This value is somewhat larger than what would be expected if a more realistic potential well was assumed, such as one with trapezoidal walls thus producing a certain diffuseness to the nuclear surface. The discrepancy between the recoil kinetic energy expectation value of 304 keV and the experimental value of the most probable recoil kinetic energy of 530 keV may not actually be real. Although the data illustrated in Fig. 3 were fitted with a straight line of zero slope between 50 and 110 $\mu g/cm^2$ of aluminum, the experimental uncertainties associated with these data could easily allow a slope of about 15% without seriously affecting the χ^2 test. The value of 304-keV recoil kinetic energy corresponds to a range of about 60 $\mu g/cm^2$ of aluminum. Secondly, the effects of refraction and absorption of the incident and outgoing nucleons on the kinetic energies and distribution of the recoiling nuclei can be appreciable.

The data in Fig. 4 indicate that the long-range Cu^{64} recoils have a similar distribution in the backward direction, but again not as discernible due to the poorer statistics of these "backward" data. Here again many more experiments are necessary to establish the backward distribution accurately. The ranges of the "step" in the backward direction are about (130±5) $\mu g/cm^2$ of aluminum to about (180±15) $\mu g/cm^2$ of aluminum, the same within experimental uncertainty as the "step" in the forward direction. The recoil kinetic energies in the backward direction are therefore essentially the same as in the forward direction and thus the interpretation is the same.

Energy Dependence

In Fig. 5 the integral recoil distribution of Cu^{65} nuclei in the forward direction produced by 130-MeV incident protons are presented. In this distribution, no "step" is discernible within the limits caused by the small number of data points determined and the normal experimental uncertainties. The number of Cu^{64} nuclei remains constant beyond absorber thicknesses of about (55±10) $\mu g/cm^2$, a somewhat larger value of the range than at 396 MeV. At 130 MeV the momentum deposition resulting from a (p,p') event is larger than at 400 MeV. Assuming zero angle scattering, a Cu^{65} recoil nucleus having 20 MeV of excitation energy has a recoil kinetic energy of about 13 keV. If the ISE mechanism is the principal mechanism at 130 MeV, then the recoil distribution illustrated in Fig. 5 is at least qualitatively in agreement with such a hypothesis.

It is of interest to compare the relative contributions of the short-range distributions and the long-range distributions for the two energies and directions at which these measurements were made. The areas under the different portions of the curves illustrated in Figs. 3, 4, and 5, normalized to common beam intensities and target thicknesses, are presented in Table II.

TABLE II. Relative numbers of short-range and long-range recoils.

	Area of low-range distribution (counts/min)	Area of high-range distribution (counts/min)
396 MeV forward direction	450± 70	440±150
396 MeV backward direction	225±100	85± 60
130 MeV forward direction	800±180	···

The data at 130 MeV could be interpreted as indicating that at this energy the ISE mechanism is the dominant mode of production. However, at 400 MeV this mechanism apparently accounts for only about 50% of the total cross section, the remaining 50% being accounted for by a knock-out mechanism. This is in reasonable agreement with the predictions of Yule and Turkevich[8] who studied this same reaction and based their conclusions on the relative numbers of the two kinds of events leading to Cu^{64} from Monte Carlo calculations. This result, however, is in serious disagreement with the results of Remsberg,[9] which would indicate a considerably lower percentage of (p,pn) events by the ISE mechanism.

The ratio of the sum of the forward area to backward area at 400 MeV is 2.87±1.21. The value of 3.3 for this ratio, determined by Merz and Caretto[2] by integral experiments, is well within the experimental uncertainty of the value quoted from these present experiments.

[7] A. A. Ross, H. Mark, and R. D. Lawson, Phys. Rev. **102**, 1613 (1956).

[8] H. P. Yule and A. Turkevich, Phys. Rev. **118**, 1591 (1960).

[9] L. P. Remsberg and J. M. Miller, Phys. Rev. **130**, 1541 (1963).

Angular Distribution

The most difficult feature of the data to understand is the ratio of the area of the short-range recoils at 400 MeV in the forward direction to that in the backward direction. The value of this ratio is 2.0 ± 1.4 (see Table II). On the basis of the ISE mechanism one would expect this ratio to be unity, or just slightly larger than unity. Since such a large experimental uncertainty exists for this number, no interpretation is warranted until further experimental work can be done.

The results of the integral angular distribution experiments at 400 MeV are illustrated in Fig. 6. The large ratio of the number of long-range Cu^{64} nuclei found in the forward direction to the number found in the backward direction (see Table II) has a value of 5.2 ± 0.8. If the point at 105° in Fig. 6 is assumed to be representative of the nearly isotropic low-energy recoils as produced by the ISE mechanism, then the recoils at angles less than and greater than 105° must be the high energy recoils produced by the knock-out mechanism. Subtraction of the "isotropic" contribution from the values listed for the total experimental angular distribution gives a forward-backward ratio of the areas of the remaining angular distributions, between 0° and 90° to that between 90° and 180°, of 7.15 ± 1.43 in reasonable agreement with the value of this ratio as determined from the differential measurements.

The same forward and backward peaking of the long-range Cu^{64} recoils is observable from the integral distribution curves of Figs. 3 and 4. The angle of the rise from the first "step" to the second "step" in Fig. 3 corresponds to the maximum angle of deflection of Cu^{64} recoils from the incident beam. This angle is about 50°, not in too serious disagreement with the angular distribution of Fig. 6.

One interesting feature of the high-energy recoil data is this rather pronounced forward-backward angular distribution. As a very first approximation one would expect the recoil angular distribution based on the clean knock-out mechanism to be nearly isotropic in the system of the moving target nucleus. According to Benioff[10] and Grover,[11] successful (p,2 nucleon) reactions must take place in localized regions of the nucleus; which regions in general can be described by a zone or band on the side of the nucleus opposite the point of entry of the incident particle. In addition to this localization of the nuclear volume in which successful (p,pn) collisions can take place, a second restriction is imposed that the collision nucleon must lie in an orbital near the top of the nuclear well in order to prevent the deposition of excessive excitation energy (>10 MeV). In the case of Cu^{65}, the collision neutron is probably either in a $2P_{3/2}$ state or in a $1f_{5/2}$ state. The observed angular distribution may be caused by, at least in part, the effect of the absorption and refraction of the incident and outgoing particles. However, as mentioned previously the slope of the curve in Fig. 3, between 50 and 110 $\mu g/cm^2$, could actually be as large as about 15% and still be within experimental statistics. In this case the high-energy Cu^{64} recoils would be observed at all angles, but the intensity of such recoils would be low at large angles. Further experimental work is underway to examine in greater detail the behavior of these high-energy recoils.

ACKNOWLEDGMENTS

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[10] P. A. Benioff, Phys. Rev. **119**, 324 (1960).
[11] J. R. Grover (private communication).