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Angular Distributions of the Recoil Nuclei from the $Cu^{65}(p,pn)Cu^{64}$ Reaction at 0.37, 1.0, and 2.8 GeV*

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Angular distributions of the recoil nuclei from the $Cu^{65}(p,pn)Cu^{64}$ reaction at incident proton energies of 0.37, 1.0, and 2.8 GeV were measured, and each was found to consist of a narrow sidewise peak on a gently sloping background. The most probable angle increases from 75° at 0.37 GeV to 85° at 2.8 GeV. The peaks are interpreted as resulting from a mechanism of inelastic scattering followed by neutron evaporation. They are thus taken to support the concept that the various mechanisms for nucleon, 2-nucleon reactions contribute independently, without interference, to the total cross sections for these reactions. The cross section in the peak was found to be about 0.3 of the total cross section at each of the three energies.

I. INTRODUCTION

THE (p,pn) reaction at high energies ($>\sim350$ MeV) has commonly been assumed to proceed through two general mechanisms: (1) clean knockout, a fast, one-step process; and (2) inelastic scattering followed by neutron evaporation (ISE), and charge-exchange scattering followed by proton evaporation (CESE). The two steps of the ISE and CESE mechanisms are thought to be well separated in time. These two-step mechanisms are considered together here because they are expected to have similar kinematic properties. These and other possible mechanisms for nucleon, 2-nucleon reactions have been discussed in detail in the review by Grover and Caretto.[1]

Various attempts have been made to estimate the relative contributions of the different mechanisms to the total cross sections for (p,pn) reactions.[1,2] Grover and Caretto have pointed out, however, that the validity of this concept of separate mechanisms, each making its independent contribution to the total cross section for a nucleon, 2-nucleon reaction has not been demonstrated. This concept implies that the matrix element for a nucleon, 2-nucleon reaction consists of a sum of terms, one for each mechanism, and that, when this sum is squared to obtain the total transition probability, all of the cross terms nearly vanish. A lack of interference between the various mechanisms proposed for nucleon, 2-nucleon reactions seems plausible but, nevertheless, has not been experimentally demonstrated.

The results of the experiments reported here, the angular distributions of the product nuclei from the $Cu^{65}(p,pn)Cu^{64}$ reaction at 0.37, 1.0, and 2.8 GeV, support the concept of "independent" mechanisms in that they appear to show clearly the separate contribution of the ISE mechanism to this reaction. In addition, these data determine the approximate contribution of the ISE mechanism to the $Cu^{65}(p,pn)Cu^{64}$ reaction at the energies investigated.

II. EXPERIMENTAL PROCEDURE

The apparatus used to obtain the angular distribution of the Cu^{64} recoil nuclei has been described by Poskanzer *et al.*[3] The only change for these experiments was that the 0.00025-in.-thick Mylar catcher foils subtended a range of angles from 5° to 95° with respect to the beam direction and that the collection interval was 10°. The solid angle subtended by each collection foil from a point at the center of the target was 0.0457 sr. The targets consisted of 0.5-in. squares of Cu^{65} (enriched to 99.6%) vacuum deposited to a thickness of 2–3 $\mu g/cm^2$ onto 25–30 $\mu g/cm^2$ Formvar films. An additional angular distribution was obtained at 2.8 GeV from targets with 6-$\mu g/cm^2$ Cu^{65} on 50-$\mu g/cm^2$ Formvar in order to estimate the effect of scattering of the Cu^{64} recoils in the target and backing. In some of the irradiations an extra 0.00025-in. Mylar foil was included under the catcher foil in order to determine the activation blank of Cu^{64} from impurities in the Mylar.

The irradiations were carried out in one of the nearly field-free straight sections of the Brookhaven cosmotron. In all but one of the irradiations the Cosmotron was operated in the "flat top" mode, in which the time rate of change of the magnetic field is reduced by a factor of about 100 just after proton acceleration is stopped. This resulted in about 15 times as many traversals of the proton beam through the target as were obtained in the one run without flat topping. An additional benefit of flat topping was that the blank corrections were reduced from less than 1% to completely negligible values. Separate irradiations were performed for obtaining data in the forward and backward directions, with overlap from 85° to 95°.

After the irradiations the catcher foils were cut into 10° segments that were separately dissolved and wet ashed in a mixture of HNO_3 and $HClO_4$ containing 10 mg of Cu carrier. The Cu fractions were separated and purified through the use of standard radiochemical procedures and mounted as CuSCN. The Cu^{64} activity was assayed with end-window, methane-flow, proportional counters that had been calibrated for Cu^{64} as a

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[1] J. R. Grover and A. A. Caretto, Ann. Rev. Nucl. Sci. **14**, 51 (1964).

[2] L. P. Remsberg and J. M. Miller, Phys. Rev. **130**, 2069 (1963).

[3] A. M. Poskanzer, J. B. Cumming, and R. Wolfgang, Phys. Rev. **129**, 374 (1963).

function of sample thickness. After the activity determinations were completed, chemical yields were determined spectrophotometrically.

III. RESULTS

The resulting angular distributions are presented in Table I. The results of the separate irradiations in the forward and backward directions have been calculated from total cross sections of 57.0, 47.5, and 47.5 mb at 0.37,[4] 1.0,[5] and 2.8 GeV,[5] respectively. The standard deviations of the values in Table I are estimated to be 4% and result from an rms combination of uncertainties of 1–2% for counting statistics, 2% for relative foil areas, 2% for counter variations, and 2% for chemical yields. There is also a systematic uncertainty of 5% between the differential cross sections in the forward and backward directions of each angular distribution because of the normalization at 90°. An additional systematic uncertainty of 5% is contributed to each of the angular distributions by the uncertainty in the total cross sections. The data at 2.8 GeV suggest that there are more recoils in the forward direction from the 6-$\mu g/cm^2$ target than from the 2-$\mu g/cm^2$ target, but this trend is well within the errors if the systematic forward-backward uncertainty is taken into account. Thus it appears that the data from the 2–3-$\mu g/cm^2$ targets are free from any significant effects of scattering in the target or backing.

A correction for the 10° resolution of the collector foils was applied to all of the data obtained with the 2–3-$\mu g/cm^2$ targets. This correction was computed at each angle from a quadratic function fit to the differential cross sections at that angle and the two immediately adjacent angles. At the ends of the angular distributions, the points at 10° and 170°, the correction was computed from the quadratic function which was obtained for the adjacent angles, 20° and 160°.[6] No resolution correction was made for the finite size of the targets. The corrected angular distributions are also presented in Table I and are plotted in Fig. 1. The largest correction is seen to be about 2%.

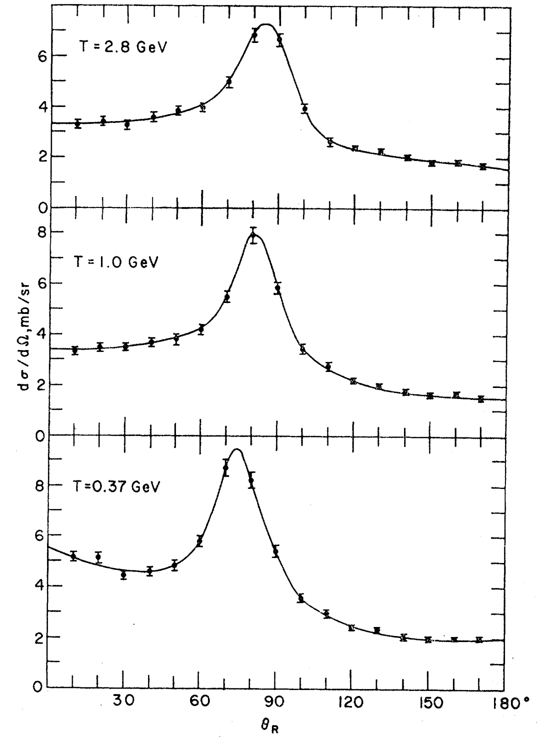

FIG. 1. Angular distributions of the recoil nuclei from $Cu^{65}(p,pn)Cu^{64}$ reaction. Corrections for the finite resolution of the catcher foils have been made.

TABLE I. Angular distributions of the recoil nuclei from the $Cu^{65}(p,pn)Cu^{64}$ reaction.

	Uncorrected $d\sigma/d\Omega$ (mb/sr)				Corrected $d\sigma/d\Omega$ (mb/sr)		
θ	$T=0.37$ GeV	$T=1.0$ GeV	$T=2.8$ GeV	$T=2.8^a$ GeV	$T=0.37$ GeV	$T=1.0$ GeV	$T=2.8$ GeV
10	5.15	3.28	3.24	3.22	5.18	3.29	3.25
20	5.12	3.48	3.37	3.56	5.15	3.49	3.38
30	4.50	3.50	3.29	3.46	4.47	3.49	3.28
40	4.61	3.67	3.56	3.72	4.60	3.67	3.56
50	4.92	3.82	3.81	3.62	4.89	3.81	3.81
60	5.91	4.19	3.98	4.30	5.84	4.15	3.94
70	8.60	5.52	5.01	4.94	8.73	5.48	4.98
80	8.15	7.76	6.78	6.63	8.24	7.93	6.86
90	5.49	5.85	6.56	6.50	5.46	5.87	6.66
100	3.66	3.49	4.00	3.90	3.61	3.42	3.95
110	2.98	2.79	2.72	3.16	2.97	2.79	2.68
120	2.49	2.21	2.40	2.34	2.48	2.20	2.39
130	2.36	2.00	2.27	2.22	2.37	2.00	2.27
140	2.07	1.80	2.06	1.97	2.06	1.80	2.06
150	1.98	1.67	1.82	1.65	1.98	1.66	1.81
160	2.00	1.69	1.81	1.67	2.00	1.70	1.82
170	1.99	1.51	1.68	1.54	1.99	1.52	1.69

[a] Target thickness $=6\ \mu g/cm^2$.

The angular distributions are characterized by prominent peaks just forward of 90°. An angular distribution of Cu^{64} recoils from the $Cu^{65}(p,pn)Cu^{64}$ reaction at 400 MeV has been reported by Reuland *et al.*,[7] which shows little resemblance to that reported here at 370 MeV. It exhibits no peak at all and instead has a broad minimum in the vicinity of 120°. This discrepancy is undoubtedly due to the very large solid angles subtended by the catchers employed by Reuland *et al.* and also to the fact that their target was oriented perpendicular to the beam direction, making it difficult for recoils at angles near 90° to leave the target without undergoing considerable scattering.

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[4] Obtained from Ref. 2 with the $Al^{37}(p,3pn)Na^{24}$ monitor cross section adjusted to conform with that in J. B. Cumming, Ann. Rev. Nucl. Sci. **13**, 261 (1963).

[5] Determined in an auxiliary experiment by the same methods employed in Ref. 2.

[6] A computer program RESOLN written by J. B. Cumming was employed.

[7] D. J. Reuland, N. K. Ganguly, and A. A. Caretto, Phys. Rev. **133**, B1171 (1964).

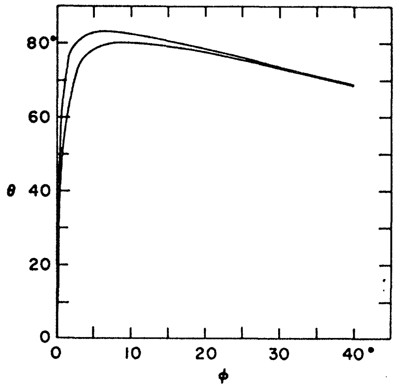

FIG. 2. Relationship between the nuclear recoil angle θ and the proton scattering angle φ for the inelastic scattering of 1-GeV protons on Cu^{65}. The upper and lower curves are calculated for excitation energies of 10 and 20 MeV, respectively, in the recoil nucleus.

IV. DISCUSSION

The three angular distributions are quite similar and their appearance is that of a fairly sharp peak on a gently sloping background. There are two interesting features of these peaks; all three have the same width of about 20° (full width at half-maximum) and the most probable angle increases with increasing incident proton energy, going from 75° at 0.37 GeV to 80° at 1.0 GeV and to 85° at 2.8 GeV. As shown in the following paragraphs, these observations suggest that the peaks are due to the ISE and/or CESE mechanisms.

The relative contributions of the ISE and CESE mechanisms to the $Cu^{65}(p,pn)$ reaction can be estimated from nuclear-evaporation theory. A Monte Carlo evaporation calculation, based on the work of Dostrovsky *et al.*,[8] was used to compute the relative prebability of neutron and proton emission from the excited Zn^{65} and Cu^{65} nuclei remaining after charge exchange and inelastic scattering from a Cu^{65} target. The ratio of the evaporation of one and only one neutron to that of one and only one proton from the excited Zn^{65} nuclei was found to range from 9 to 13, depending only weakly on the spectrum of excitation energies assumed. The same ratio for the excited Cu^{65} nuclei was about 100. Thus, only $\sim 10\%$ of the charge exchange scattering leading to the emission of one nucleon results in the (p,pn) reaction, while virtually all of the equivalent inelastic scattering yields the (p,pn) reaction product. The data compiled by Grover and Caretto[1] indicate that the cross section for inelastic scattering of high-energy protons by medium-weight nuclei, leading to the evaporation of one nucleon, is about the same or slightly larger than the corresponding cross section for charge exchange scattering. Thus it is estimated that the contribution of the CESE mechanism to the $Cu^{65}(p,pn)$ reaction is less than $\sim 10\%$ that of the ISE mechanism.[9]

That the ISE mechanism should produce a narrow, sidewise peak in the angular distribution can be shown from the relativistic two-body kinematics of inelastic scattering. When high-energy protons are scattered inelastically by nuclei with low energy transfer from the proton to the recoil nucleus, conservation of momentum and energy require that, except for very small proton scattering angles, practically all nuclei recoil into a narrow range of angles in the sidewise direction. This is illustrated in Fig. 2, which is a plot of the nuclear recoil angle as a function of the inelastic proton scattering angle for 1-GeV protons on Cu^{65}. The upper curve was calculated for an excitation energy of 10 MeV, the approximate threshold for neutron evaporation, and the lower curve for 20 MeV, the excitation energy above which 2-neutron emission becomes more probable than 1-neutron emission. Thus inelastic scattering which results in the (p,pn) reaction is restricted to the region between the two lines, and, unless the inelastic scattering is very sharply peaked forward, practically all of the nuclear recoils will have angles near the maximum. Azhgirei *et al.*[10] have measured proton spectra at several angles from the 660-MeV proton bombardment of copper, and the angular distribution of those outgoing protons with an energy decrease of between 10 and 20 MeV is peaked at about 12° with little contribution at very small angles.

The maximum nuclear recoil angles for excitation energies of 10 and 20 MeV were calculated as a function of incident proton energy and are shown in Fig. 3. Smooth backgrounds were subtracted from the peaks in Fig. 1, and the midpoints of the resultant peaks are plotted in Fig. 3. Grover and Caretto[1] have transformed the above-mentioned inelastic scattering data of Azhgirei *et al.*[10] into an angular distribution of recoil Cu^{64} nuclei at 660 MeV and have obtained a narrow, sidewise peak, the midpoint of which is also plotted in Fig. 3. All of the experimental points including that obtained from inelastic scattering data fall on the curve calculated for an excitation energy of 20 MeV. This does not imply that an excitation energy of 20 MeV is favored, however, since the average angle for all events with a given excitation energy would be expected to be a little less than the maximum angle for that excitation energy. Grover and Caretto[1] obtained a peak width of only $\sim 4°$ for the recoiling Cu^{65} nuclei after the inelastic scattering, and they estimated that the subsequent neutron evaporation would broaden the peak to $\sim 17°$, which is indistinguishable from the experimental widths of $\sim 20°$ for the peaks in Fig. 1. Thus both the positions and the widths of the peaks in the $Cu^{65}(p,pn)Cu^{64}$ angular distributions have all the characteristics expected from the ISE mechanism.

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[8] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1960).

[9] J. R. Grover and A. A. Caretto (Ref. 1) obtain a value of 5% for this ratio.

[10] L. S. Azhgirei, I. K. Vzorov, V. P. Zrelov, M. G. Meshcheryakov, B. S. Neganov, R. M. Ryndin, and A. F. Shabudin, Zh. Eksperim. i Teor. Fiz. **36**, 1631 (1959) [English transl.: Soviet Phys.—JETP **9**, 1163 (1959)].

It should be emphasized, as pointed out by Grover and Caretto,[1] that the above analysis is based solely on relativistic two-body kinematics and is therefore totally independent of any mechanism or model of inelastic scattering. ISE mechanisms involving pion production, namely $(p,p\pi^0)$, followed by neutron evaporation, do not contribute to the peaks, however, because the maximum nuclear recoil angle for the $(p,p\pi^0)$ reaction allowed by conservation laws is less than that for the (p,p') reaction and also because the nuclear-recoil angles are distributed more or less uniformly between the maximum angle and 0° because of the variable effective mass of the outgoing pion-proton system.

The total cross sections within these ISE peaks were obtained by subtracting a straight-line background and integrating the remainder. The results are listed in Table II. The upper and lower limits on the cross sections obtained from the areas under the peaks are not statistical uncertainties but represent values obtained by subtracting the smallest and largest backgrounds that could be drawn with no minimum or maximum, respectively, in the vicinity of the peak. The magnitudes of the cross sections contributed by the ISE mechanism are surprisingly large, a factor of 2 or more larger than the previous estimate of Remsberg and Miller for the $Cr^{52}(p,pn)Cr^{51}$ and $Fe^{56}(p,pn)Fe^{55}$ reactions at 380 MeV,[2] but consistent with the estimate of 20% for the $Cu^{65}(p,pn)Cu^{64}$ reaction obtained by Grover and Caretto[1] from the data of Azhgirei *et al.* at 660 MeV.[10] Benioff and Person[11] have calculated an angular distribution for the $Cu^{65}(p,pn)Cu^{64}$ reaction at 450 MeV for the clean knockout mechanism only. Their calculated angular distribution has no sidewise peak and is more or less flat in the region in which the experimental angular distributions show peaks. This calculated curve is in fact qualitatively similar to that used for the maximum background subtraction and, to the extent that it is a good representation of the background at all three incident energies, the lower limits in Table II would be the best estimates of the cross sections contributed by the ISE mechanism.

Another surprising feature of the data in Table II is the constancy of the cross section for the ISE process over a wide range of bombarding energies T, while Grover and Caretto[1] found an approximate $1/T$ dependence for this mechanism in the interval of 100 to ~600 MeV. This flattening out of the energy dependence of the ISE process at high energies can probably be explained in terms of a model in which inelastic scattering leading to 10–20 MeV of excitation energy occurs when the incident proton makes a single, low-momentum-transfer collision with a nucleon in the nucleus, and the collision partner is captured. The increased forward peaking of the angular distributions of proton-nucleon elastic scattering at high energies favors low-momentum-transfer collisions. Angular distributions[12–14] for free proton-proton elastic scattering have been transformed into squared momentum transfer distributions and plotted in Fig. 4. The inelastic scattering data of Azhgirei *et al.*[10] indicate that most of the resultant Cu^{65} nuclei with excitation energies of 10–20 MeV will have a recoil kinetic energy between ~0.25 and ~1 MeV. It is just at momentum transfers equivalent to these kinetic energies that the differential cross sections at all three energies in Fig. 4 are about the same.

One cannot, of course, rule out the possibility that a sidewise peak may also be contributed by the clean knockout mechanism. However, it seems unlikely that such a peak could be as narrow as 20°, and it is highly improbable that the angles of such peaks would change with bombarding energy in exactly the same way as those due to the ISE mechanism. On this basis, then, one can conclude that relatively little of the peaks are due to the clean knockout mechanism.

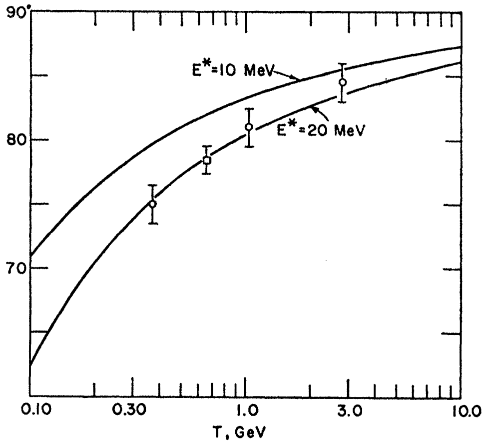

FIG. 3. The circles are the midpoints of the peaks in Fig. 1 after background subtraction; the square is the midpoint of the peak obtained from transformation of the inelastic scattering data in Ref. 10 by Grover and Caretto (Ref. 1). The lines give the relationship between the maximum nuclear recoil angle and the incident proton energy for two values of the excitation energy of the recoil nucleus.

TABLE II. Separation of total $Cu^{65}(p,pn)Cu^{64}$ cross sections into contributions from peaks and "background."

	$T=0.37$ GeV	$T=1.0$ GeV	$T=2.8$ GeV
σ_{tot} (mb)	57.0	47.5	47.5
σ_{peak} (mb)	$16.1_{-5.2}^{+8.1}$	$16.5_{-6.2}^{+5.1}$	$15.6_{-3.4}^{+1.8}$
σ_{bkg} (mb)	40.9	31.0	31.9
$\sigma_{peak}/\sigma_{tot}$	$0.28_{-0.09}^{+0.14}$	$0.35_{-0.13}^{+0.10}$	$0.33_{-0.07}^{+0.04}$

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[11] P. A. Benioff and L. W. Person, Phys. Rev. **140**, B844 (1965).

[12] Holt, Hortung, and Moore, quoted in W. N. Hess, Rev. Mod. Phys. **30**, 368 (1965).

[13] D. V. Bugg, A. J. Oxley, J. A. Zall, J. G. Rushbrooke, V. E. Barnes, J. B. Kinson, W. P. Dodd, G. A. Doran, and L. Riddiford, Phys. Rev. **133**, B1017 (1964).

[14] T. Fujii, G. B. Chadwick, G. B. Collins, P. J. Duke, N. C. Hien, M. A. R. Kemp, and F. Turkot, Phys. Rev. **128**, 1836 (1962).

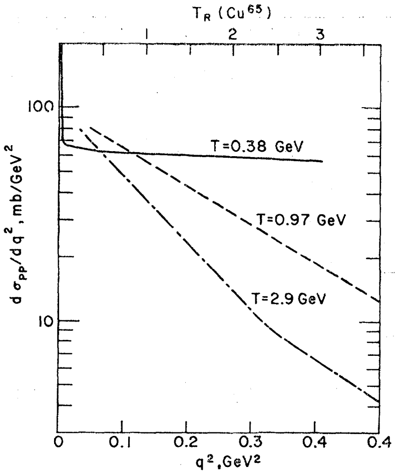

FIG. 4. Differential proton-proton elastic-scattering cross section as a function of the squared momentum transfer. The data at 0.38, 0.97, and 2.9 GeV come from Refs. 12, 13, and 14, respectively. The upper abscissa is the equivalent Cu^{65} recoil kinetic energy in MeV.

The angular distribution of C^{11} recoils from the C$^{12}(p,pn)$C^{11} reaction at 450 MeV has been reported by Panontin *et al.*[15] A sharp, sidewise peak was not observed in that angular distribution, although it was estimated that the ISE and CESE mechanisms together may contribute ~15% of the total C$^{12}(p,pn)$C^{11} cross section at 450 MeV. Panontin *et al.* stated that the precision of their experiment does not permit definite conclusions as to the presence or absence of a sidewise peak. However, it should be pointed out that the broadening of the peak due to neutron evaporation from excited C^{12} nuclei would be about twice that from excited Cu^{65} nuclei because the momentum transfer in the inelastic scattering of 660 MeV protons from carbon is only about 60% of that from copper,[10] and also because the energy of the evaporated neutrons is probably higher from the lighter carbon nucleus. A peak with a width of ~40° would be difficult to resolve from a sloping background even with fairly precise data.

The relatively large contribution of the ISE mechanism to the Cu$^{65}(p,pn)$Cu^{64} reaction has serious implications for analyses of high-energy (p,pn) cross sections that are based solely on the clean knockout mechanism. Porile and Tanaka[16] have observed variations in (p,pn) cross sections obtained from the bombardment of targets ranging from Cu^{65} to Br^{81} by 3-GeV protons which they have interpreted as being correlated with the availability of the $1f_{7/2}$ neutron shell to the (p,pn) reaction through the clean knockout mechanism. Their analysis was based in part on the calculations of Benioff,[17] which includes the clean knockout mechanism plus only a ~5% contribution from an ISE mechanism. The maximum variation in the (p,pn) cross sections is about the same as the ISE contribution to the Cu$^{65}(p,pn)$ cross section. Nothing is known about the variation of the ISE cross sections with neutron or proton number, but it is known that cross sections for the $(p,2n)$ reaction, which most probably proceed primarily through the related CESE mechanism, exhibit large and unpredictable variations.[1]

V. CONCLUSIONS

The peaks in the Cu$^{65}(p,pn)$Cu^{64} angular distributions are ascribed to the ISE mechanism for the (p,pn) reaction solely on the basis of two-body kinematics and without recourse to any model of inelastic scattering although some contribution to these peaks from the clean knockout mechanism cannot be entirely ruled out. Thus the observation of these peaks supports the concept of independent mechanisms for high-energy nucleon, 2-nucleon reactions, each with its separate contribution to the total cross section. The contribution of the ISE mechanism to the Cu$^{65}(p,pn)$Cu^{64} reaction is relatively large, ~30% of the total, and independent of incident proton energy from 0.37 to 2.8 GeV in contrast to the $1/T$ dependence found for incident proton energies from 100 to 400 MeV.[1]

ACKNOWLEDGMENTS

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[15] J. A. Panontin, L. L. Schwartz, A. F. Stehney, E. P. Steinberg, and L. Winsberg, Phys. Rev. **145**, 754 (1966); **169**, 841 (1968).

[16] N. T. Porile and S. Tanaka, Phys. Rev. **130**, 1541 (1963).

[17] P. A. Benioff, Phys. Rev. **119**, 324 (1960).