An empirical relationship between static and transition quadrupole moments on one hand and the variable moment of inertia on the other has been obtained. The ratios $E_2'/E_2$ and $B(E2, 2'\rightarrow 2)/B(E2, 2\rightarrow 0)$ were found to be related to $E_4/E_2$, and thus to $\sigma$.

It could further be shown that even a band of a nucleus displaying a particularly complex behavior in terms of the microscopic analysis of Kumar and Baranger,[43] such as $Pt^{194}$, is accurately described by the VMI model.

In view of the foregoing, it may be expected that an analysis of the two parameters ($\mathcal{I}_0$ and $\sigma$) obtained from this one-variable ($\mathcal{I}$) model will lead to greater insight into nuclear dynamics.

## ACKNOWLEDGMENTS

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# Production of $In^{111}$ and $In^{114m}$ from the Separated Isotopes of Cadmium Using 70- to 400-MeV Protons*†

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The cross sections for the $Cd^{110+x}(p, xn)In^{111}$ and the $Cd^{113+x}(p, xn)In^{114m}$ reactions at proton energies from 70 to 400 MeV have been measured using the separated isotopes of cadmium as targets. The energy dependence of the $(p, n)$, $(p, 2n)$, and $(p, 3n)$ reactions is inversely proportional to the incident energy over the entire energy region, while the $(p, 4n)$ and $(p, 6n)$ reactions exhibit this energy dependence only above 150 MeV. This similar energy dependence of the $(p, xn)$ reactions supports the conclusion that these reactions take place by the same mechanism: a $p$-$n$ cascade step followed by the evaporation of $x-1$ neutrons. The change in the energy dependence of the $(p, 4n)$ and $(p, 6n)$ reactions below 100 MeV is probably due to contributions from compound-nucleus processes. The experimental results are compared with Monte Carlo cascade and evaporation calculations.

## INTRODUCTION

THE production of $In^{111}$ and $In^{114m}$ was studied as a function of incident proton energy from targets consisting of the separated cadmium isotopes. Unlike other studies of $(p, xn)$ reactions which generally involve the production of a different product from the same target with each change in $x$, in this work the production of the same products $In^{111}$ and $In^{114m}$ from the separated target isotopes of cadmium eliminates uncertainties in decay schemes and detection methods in the calculation of relative cross sections.

As discussed by Church and Caretto[1], the most plausible mechanism for $(p, xn)$ reactions involves a $(\tilde{p}, \tilde{n})$ cascade[2] leading to sufficient residual excitation energy such that $(x-1)$ neutrons can be evaporated. Since the evaporation process is sensitive to nucleon binding energies, Coulomb barriers, and shell effects, while the cascade is generally insensitive to these effects, the results of the study of the type of $(p, xn)$ reactions reported here should be nearly exclusively dependent on the cascade part of the interaction.

Thus, the mechanism should involve a $p$-$n$ scattering or charge exchange such that the proton is scattered at large center of mass angles for $(p, n)$ reactions. The residual excitation energy $E^*$ is given by $E^*=E_p+E_f-E_j$, where $E_p$ is the recoil kinetic energy of the proton scattered through a center-of-mass scattering angle $\theta$ near 180°, $E_f$ the nucleon kinetic energy at the top of the Fermi sea, and $E_j$ the neutron kinetic energy prior to collision. In order that $E^*$ be large enough so that $x-1$ neutrons are energetically allowed

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[1] L. B. Church and A. A. Caretto, Jr., Phys. Rev. **178**, 1732 (1969).

[2] Specific nucleonic cascades are represented by letters with tildes, such as $(\tilde{p}, \tilde{n})$, $(\tilde{p}, 2\tilde{n})$, etc. The over-all nuclear reaction is designated by the plain letters.

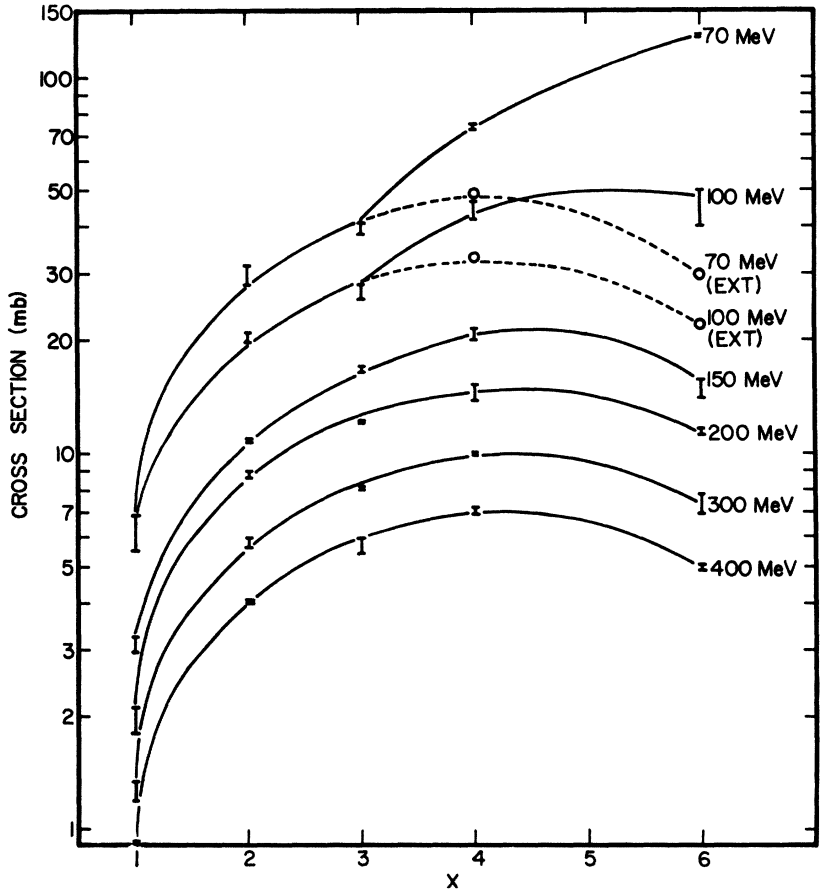


FIG. 1. Results of the $Cd^{110+x}(p, xn)In^{111}$ reactions at 70 to 400 MeV. Dashed lines at 70 and 100 MeV were drawn to be similar to the higher-energy data. See text for explanation.

to evaporate, successively larger values of $E_p$ are required as $x$ increases, which in turn requires smaller values of $\theta$ (in the second quadrant).

An alternative mechanism for high energy $(p, xn)$ reactions involves the cascades of the type $(\tilde{p}, 2\tilde{n})$ or $(\tilde{p}, 3\tilde{n})$ followed by $\gamma$ deexcitation. Cascades of the type $(\tilde{p}, (x-y)\tilde{n})$ followed by the evaporation of $y$ neutrons must also be considered. The number of events of these types, as predicted by various Monte Carlo cascade calculations,[3,4] is very small, particularly for $x-y>1$.

Since the elementary $p$-$n$ cross section varies approximately as $E^{-0.5}$ to $E^{-1}$ in the energy region of 100 to 400 MeV, it is anticipated that $(p, xn)$ reactions, at least for small $x$, should have a similar energy dependence. At incident energies below 100 MeV, reactions such as $(p, 4n)$ and $(p, 6n)$ may take place primarily by compound nucleus events.

Values of the cross section of $(p, xn)$ reactions for the production of $In^{111}$ $(0<x\leq 6)$, and $In^{114}$ $(0<x\leq 3)$ are reported. These values are compared with the results from Monte Carlo cascade and evaporation calculations.

TABLE I. Target materials and composition of separated isotopes as received from Oak Ridge (%).

| Target isotope | $Cd^{111}$ | $Cd^{112}$ | $Cd^{113}$ | $Cd^{114}$ | $Cd^{116}$ |
|---|---|---|---|---|---|
| % Natural abundance | 12.75 | 24.07 | 12.26 | 28.86 | 7.58 |
| $Cd^{106}$ | 0.05 | 0.02 | 0.01 | 0.01 | 0.03 |
| $Cd^{108}$ | 0.05 | 0.02 | 0.01 | 0.01 | 0.02 |
| $Cd^{110}$ | 0.63 | 0.13 | 0.15 | 0.07 | 0.21 |
| $Cd^{111}$ | 96.5 | 0.35 | 0.26 | 0.09 | 0.24 |
| $Cd^{112}$ | 1.84 | 98.5 | 1.01 | 0.26 | 0.53 |
| $Cd^{113}$ | 0.44 | 0.44 | 96.3 | 0.33 | 0.37 |
| $Cd^{114}$ | 0.59 | 0.55 | 2.13 | 99.1 | 1.44 |
| $Cd^{116}$ | 0.05 | 0.07 | 0.15 | 0.07 | 97.2 |

## EXPERIMENTAL

Targets were bombarded in the internal proton beam of the Carnegie-Mellon University synchro-

[3] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 185 (1958).
[4] K. Chen, Z. Fraenkel, G. Friedlander, J. R. Grover, J. M. Miller, and Y. Shimamoto, Phys. Rev. **166**, 949 (1968).

TABLE II. Experimental absolute cross-section values in millibarns and incident proton energy in MeV.

| Reaction | 50 | 70 | 100 | 150 | 200 | 300 | 400 |
|---|---|---|---|---|---|---|---|
| $Cd^{111}(p, n)In^{111}$ | | 6.55±0.45 (4)[a] | 5.96±0.34 (2) | 3.11±0.16 (2) | 1.96±0.15 (2) | 1.27±0.06 (2) | 0.92±0.01 (2) |
| $Cd^{112}(p, 2n)In^{111}$ | 77.8±12.8 (2) | 29.7 ±1.9 (2) | 20.4 ±0.6 (2) | 10.8 ±0.1 (2) | 8.83±0.18 (3) | 5.86±0.11 (2) | 4.05±0.22 (4) |
| $Cd^{113}(p, 3n)In^{111}$ | | 39.5 ±1.7 (2) | 26.7 ±1.2 (2) | 16.7 ±0.3 (2) | 12.3 ±0.1 (2) | 8.15±0.10 (2) | 5.77±0.21 (2) |
| $Cd^{114}(p, 4n)In^{111}$ | | 74.4 ±0.3 (2) | 44.3 ±3.5 (3) | 20.7 ±0.8 (2) | 14.5 ±0.8 (3) | 10.1 ±0.1 (2) | 7.12±0.21 (2) |
| $Cd^{116}(p, 6n)In^{111}$ | | 129.0 ±1.0 (2) | 45.2 ±5.5 (3) | 14.9 ±0.8 (3) | 11.6 ±0.4 (2) | 7.40±0.46 (3) | 6.01±0.05 (2) |
| $Cd^{114}(p, n)In^{114m}$ | | 4.29±0.09 (2) | 3.45±0.09 (3) | 2.02±0.08 (2) | 1.41±0.08 (3) | 0.98±0.03 (2) | 0.83±0.05 (2) |
| $Cd^{116}(p, 3n)In^{114m}$ | | 28.6 ±0.3 (2) | 19.3 ±2.0 (3) | 9.15±0.46 (3) | 7.59±0.18 (2) | 4.89±0.20 (3) | 4.26±0.03 (2) |
| $Cd(p, xn)In^{111}$ | | | | | | | 6.37±0.13 (2) |

[a] The numbers in parentheses represent the number of independent determinations.

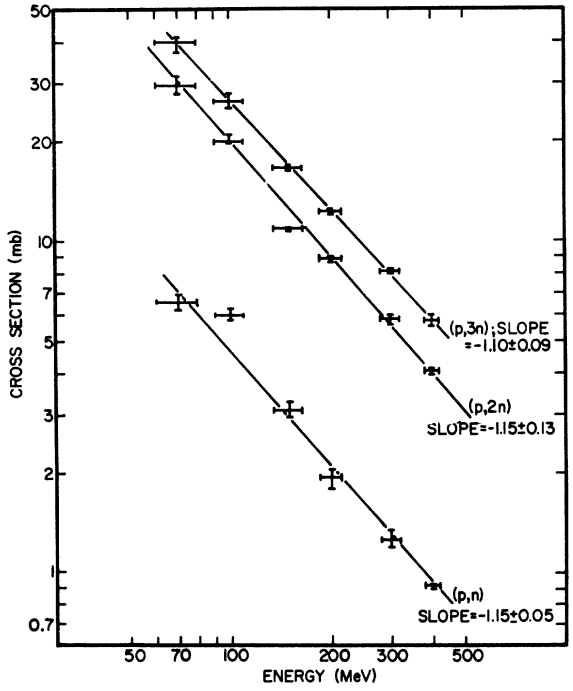


FIG. 2. Excitation function for the $Cd^{111-113}(p, 1-3n)In^{111}$ reactions from 70 to 400 MeV.

cyclotron at energies from 70 to 400 MeV obtained by appropriate radial placement of the target. The uncertainty of the proton energy has been estimated as being less than ±5% at 400 MeV and ~±15% at 70 MeV. Irradiations were of 30- to 60-min duration depending on the nature of the particular system being studied.

All the targets consisted of a pellet composed of 0.5 to 2 mg of a separated cadmium isotope, as the oxide, and 120 to 200 mg of 99.99% pure aluminum powder. These pellets were prepared by weighing the

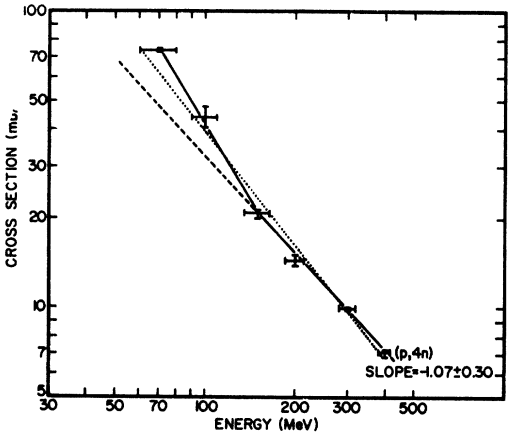


FIG. 3. Excitation function for the $Cd^{114}(p, 4n)In^{111}$ reaction from 70 to 400 MeV. See text for explanation of dotted and dashed lines.

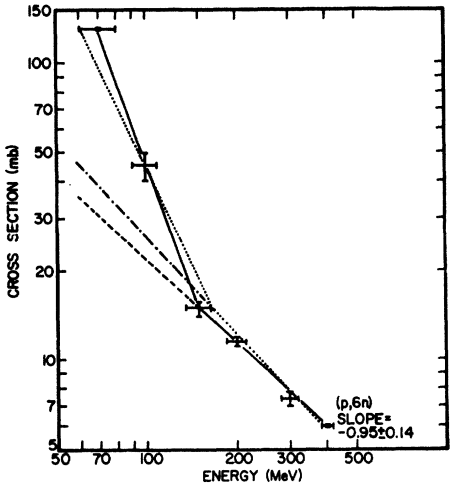


FIG. 4. Excitation function for the $Cd^{116}(p, 6n)In^{111}$ reaction from 70 to 400 MeV. See text for explanation of nonsolid lines.

isotope and the aluminum powder in a plastic capsule and shaking the mixture with a plastic ball on a "Wig-1-Bug" vibrator. The resulting homogeneous mixture was compacted into a 1.5- by 2-cm pellet by using a specially designed mold on a hydraulic press. A list of the composition of the cadmium isotopes used is given in Table I.

After irradiation the targets were dissolved in the presence of appropriate carriers and chemically purified using adaptions of standard radiochemical procedures.[5] The chemical yield was determined gravimetrically by weighing the 8-hydroxyquinoline complex of indium.

In all cases, cross sections were measured relative to that of the $Al^{27}(p, 3pn)Na^{24}$ monitor reaction, using the values of the cross section suggested by Cumming.[6] The targets were a stack consisting of a guard foil, a monitor foil, the target pellet, another monitor foil, and another guard foil. The upstream and downstream monitor foil activities differed by no more than $\pm 3\%$ and this agreement is considered as evidence for the proper alignment of the target.

The disintegration properties of $In^{111}$ and $In^{114m}$ were taken from the Nuclear Data Sheets.[7] The 247-keV $\gamma$ rays of $In^{111}$ and the 191-keV $\gamma$ rays of $In^{114m}$ were detected with a 3×3-in. NaI(Tl) crystal connected via a photomultiplier tube to a multichannel analyzer. Heath's[8] values were used to calibrate this crystal. A least-squares analysis of all the decay curves was performed with the aid of a digital computer.

[5] W. J. Nieckarz, Jr., Ph.D. thesis, Carnegie Institute of Technology, 1966 (unpublished).
[6] J. B. Cumming, Ann. Rev. Nucl. Sci. **13**, 261 (1963).
[7] *Nuclear Data Sheets*, compiled by K. Way *et al.* (The National Academy of Sciences–National Research Council, Washington, D.C. 20025, 1965).
[8] R. L. Heath, USAEC Research and Development Report No. IDO-16880-1, 1964 (unpublished).

Since it was not possible to obtain isotopes enriched to 100%, it was necessary to correct for the contamination of other isotopes present in each sample. This correction was accomplished by solving simultaneous equations of the form $\sum_M P_M{}^N \sigma_M = \sigma_N$, where $\sigma_N$ is the observed cross section from mixture Cd-$N$, $\sigma_M$ is the true cross section from isotope $Cd^M$, and $P_M{}^N$ is the percent of isotope $Cd^M$ in mixture Cd-$N$. The symbols $M$ and $N$ each take the values 111, 112, 113, 114, and 116. The error in the true cross section $\sigma_M$ due to the contamination of other isotopes was thus reduced to less than 1%.

As a check on the results obtained from the different separated isotopes of cadmium, a foil of natural cadmium was irradiated at 400 MeV. The cross section for the production of $In^{111}$ from natural cadmium was found to be $6.37 \pm 0.13$ mb. This value can be compared to the cross section obtained from the summation of the individual contributions for the separated cadmium isotopes and weighted according to their natural abundances. This calculation gave a value of $5.81 \pm 0.29$ mb. The close agreement of these two numbers indicates that the pellet molding technique employed for making the targets of the separated isotopes was valid within the uncertainties cited.

## RESULTS

The experimentally determined cross sections are presented in Table II. The uncertainties listed are the root-mean-square deviations from the average for identical determinations. The energies quoted are the calculated kinetic energies of the proton beam taking into consideration the radial placement of

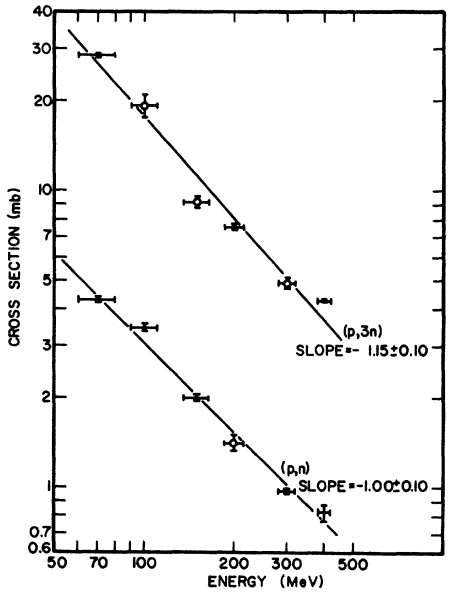


FIG. 5. Excitation functions for the $Cd^{114,116}(p, 1, 3n)In^{114m}$ reactions from 70 to 400 MeV.

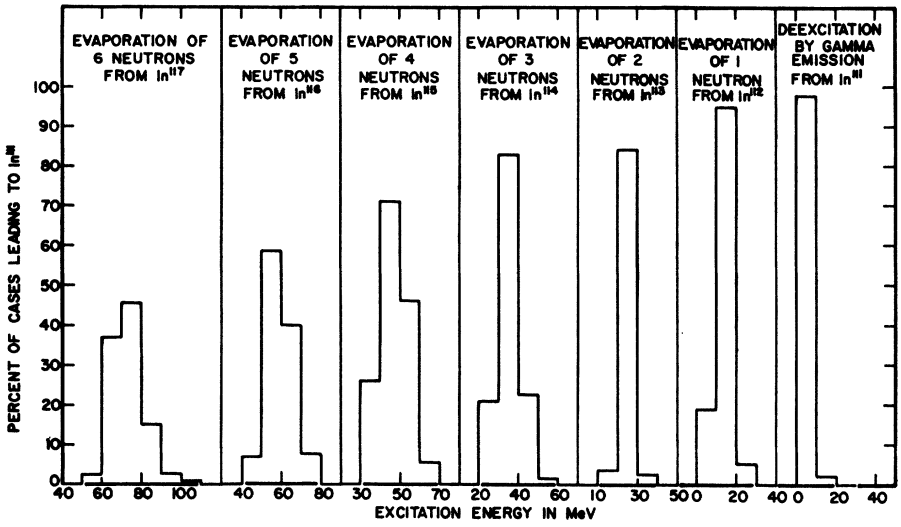


FIG. 6. Probabilities of producing $In^{111}$ from the various indium nuclides at different excitation energies according to Monte Carlo evaporation calculations.

the target and the magnetic field strength. In addition, there are systematic uncertainties of about ±8% for the monitor cross section, ±3% for target alignment, ±5% for decay curve resolution, ±3% for pellet preparation, ±3% for chemical yield determination, and ±5% for crystal calibration. The $In^{114m}$ system also had a ±10% uncertainty due to the uncertainty in the conversion coefficient of the 191-keV $\gamma$ ray. The value of $e/\gamma$ used was 4.25±0.4.[9] The over-all uncertainty, taken to be the geometric mean of the individual uncertainties was ±12% for the $In^{111}$ system and ±16% for the $In^{114m}$ system.

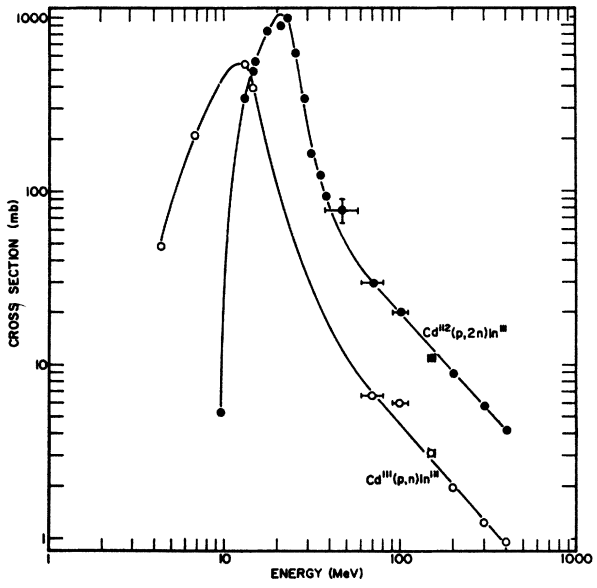


FIG. 7. Excitation function for the $Cd^{111}(p, n)In^{111}$ and $Cd^{112}(p, 2n)In^{111}$ from 4 to 400 MeV.

[9] D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).

The measurement of the cross sections of reactions at high energies which have large cross sections at low energies, such as $(p, n)$ and $(p, 2n)$ reactions, is sensitive to low-energy secondary particles. The target packets used in this study had a total upstream surface density of less than 100 mg $cm^{-2}$. Church[10] has shown that for targets similar to those used in this study, the observed $(p, 2n)$ reaction cross section is approximately independent of target thickness from 20 to 220 mg $cm^{-2}$; however, the $(p, n)$ reaction cross section exhibits a 13% increase per 100 mg $cm^{-2}$ of target material. This latter number is in close agreement with the value of an 18% increase per 100 mg $cm^{-2}$ of target material obtained by Koch[11] for the $Ni^{64}$ $(p, n)$ $Cu^{64}$ reaction. In view of the uncertainties involved in extrapolating these thickness dependency curves to zero thickness, no thickness corrections were applied to the data and these uncertainties have not been included in the total uncertainties assigned to these cross sections.

## DISCUSSION

The results of the $Cd^{110+x}(p, xn)In^{111}$ study are illustrated in Fig. 1, in which solid lines connect points measured at the same incident energy. The family of curves thus produced are similar from 70 to 400 MeV for $x \leq 3$ and at all values of $x$ for energies above 100 MeV. The extrapolated curves (dashed lines) at 70 and 100 MeV are discussed later.

The excitation functions for the $(p, xn)$ reactions are plotted in Figs. 2, 3, and 4. The energy uncertainties indicated are estimates of the proton energy resolution at the various radial positions of the target. Figure 2

[10] L. B. Church, Ph.D. thesis, Carnegie Institute of Technology, 1966 (unpublished).

[11] R. C. Koch, Ph.D. thesis, University of Chicago, 1955 (unpublished).

TABLE III. Comparison of experimental results and estimates based on compound-nucleus mechanism.

| Target nucleus | $Cd^{114}$ | | $Cd^{116}$ | |
|---|---|---|---|---|
| Proton energy | 70 | 100 | 70 | 100 |
| Energy of compound nucleus | 60–80 | 90–110 | 60–80 | 90–110 |
| Experimental | | | | |
| Measured cross section (mb) | 73 | 44 | 126 | 45 |
| Extrapolated cascade contribution $\sigma(\tilde{p}, \tilde{n})$ | 73–48 | 44–33 | 39–30 | 26–22 |
| Compound nucleus contribution $\sigma_{CN}$ | 0–25 | 0–11 | 87–96 | 19–23 |
| Estimate based on Monte Carlo cascade calculation | | | | |
| Opacity (0.9×geometric cross section) | 1123 | 1123 | 1136 | 1136 |
| Probability of compound-nucleus formation $P_{CN}$ | 0.22 | 0.07–0.12 | 0.22 | 0.07–0.12 |
| Probability of evaporation to product $P_E$ | 0.05 | 0 | 0.45 | 0.08 |
| Compound-nucleus contribution $\sigma_{CN}$ | 12 | 0 | 112 | 6–10 |

is a plot of log $\sigma$ versus log $E$ for the $Cd^{110+x}(p, xn)$ $In^{111}$ reactions, where $x=1$, 2, and 3. The least-squares slope for all three lines is $-1.1\pm0.1$. This value is within the range of values for the exponent in the energy dependence of the free-nucleon $p$-$n$ scattering data in this energy region from $E^{-1.5}$ to $E^{-0.5}$ and is in agreement with the trend in the energy dependence of $(p, n)$ reactions observed[12] for other targets.

The $(p, n)$ reaction between 100 and 400 MeV takes place by $(\tilde{p}, \tilde{n})$ cascades in which the residual excitation energy is too low for neutron evaporation to occur. The similarity of the $(p, 2n)$ and $(p, 3n)$ excitation functions with that of the $(p, n)$ reaction implies that the same mechanism dominates. For the $(p, 2n)$ and $(p, 3n)$ reactions, the proton is scattered into successively smaller center-of-mass scattering angles $\theta$ which results in larger residual excitation energies. Thus, it will be possible to evaporate successively one, two, or up to $x-1$ neutrons as $\theta$ decreases from $\pi$ to $\pi/2$. In each case, the scattering of the proton into that band of energies such that $x-1$ neutrons can evaporate is approximately inversely proportional to the first power of the incident energy.

Figures 3 and 4 illustrate the excitation functions, plotted in the same way, for the $(p, 4n)$ and $(p, 6n)$ reactions to produce $In^{111}$. The data no longer exhibit the linear behavior observed for the $(p, n)$, $(p, 2n)$, and $(p, 3n)$ cases. The high-energy portions of the $(p, 4n)$ and $(p, 6n)$ curves, $E_i \geq 150$ MeV do exhibit the same straight lines which have least-squares slopes of $-1.07\pm0.30$ and $-0.95\pm0.14$, respectively, in good agreement with the values of the slopes of the $(p, n)$, $(p, 2n)$, and $(p, 3n)$ excitation functions. In Figs. 3 and 4 the solid lines represent the best fit of the data. The low-energy points 70 to 150 MeV could be fitted equally well with a curved line. The dotted line illustrates the extreme case where all the data have the maximum allowable uncertainties.

Figure 5 is a plot of log $\sigma$ versus log $E_i$ for the $Cd^{114}(p, n)In^{114m}$ and $Cd^{116}(p, 3n)In^{114m}$ reactions. The least-squares slope for the $(p, 3n)$ reaction is $-1.15\pm0.10$ and $-1.00\pm0.10$ for the $(p, n)$ reaction. The energy dependence for these reactions is about the same $(-1.0\pm0.1)$ as for the $(p, xn)$ reactions producing $In^{111}$.

The excitation energies involved in the evaporation of three to five neutrons are comparable to the excitation energies resulting from compound nucleus processes at the lowest incident energies. An evaporation program model after that of Dostrovsky *et al.*,[13] but written[14] for the Carnegie-Mellon University Control Data G-21 computer, was used to calculate the probability that a nucleus with a given amount of excitation energy would evaporate the necessary number of neutrons to produce $In^{111}$. Figure 6 shows the results of this calculation. Since most of the nuclides listed are neutron rich, it is not surprising that the ratio of neutrons evaporated to charged particles emitted is high. Even the evaporation of six neutrons from $In^{117}$ has a probability of about 0.45 at an excitation energy between 70 and 80 MeV.

At low bombarding energies, 70 to 100 MeV, the total deposition energy via compound nucleus processes is only slightly larger than the peak energy in the excitation energy spectrum leading to the evaporation

[12] W. J. Tretyl and A. A. Caretto, Jr., Phys. Rev. **146**, 836 (1966).

[13] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).

[14] F. M. Kiely (private communication).

of four, at 70 MeV, or six neutrons at 100 MeV. Assuming that compound-nucleus processes contribute to the $(p, 4n)$ and $(p, 6n)$ cross section at incident energies equal to or less than 100 MeV, the dashed lines in Figs. 3 and 4 are extrapolations to low energies of the high-energy straight-line portion of these excitation functions. These extrapolated values, replotted also in Fig. 1 as the dashed curves, can be interpreted as representing the contribution to the total $(p, xn)$ cross section from charge exchange scattering processes at these lower energies. The difference of these extrapolated values from the experimental cross sections may represent the contribution to the cross section of compound-nucleus processes. It should be noticed that the dashed curves illustrated in Fig. 1 make up a smooth family of curves for $\sigma$ $(p, xn)$ versus $x$ from 70 to 400 MeV.

The results of the Monte Carlo cascade calculations of Jackson[15] and Metropolis *et al.*[3] indicate that the percent of the incident particles leading to compound-nucleus formation range from 12% to 7% at 100 MeV and about 22% at 70 MeV. Results of the Vegas Monte Carlo cascade calculations[4] are consistent with these estimates. Even a few percent of the interactions leading to compound-nucleus formation is sufficient to affect the $(p, xn)$ cross section at low energies thus influencing the energy dependence. The fraction of compound-nucleus events at deposition energies around 70–80 or 100–110 MeV which deexcite to produce $In^{111}$ are illustrated in Fig. 6.

The compound nucleus formed by a proton incident on $Cd^{116}$ or $Cd^{114}$ would be $In^{117}$ and $In^{115}$, respectively. The excitation energy would be the sum of the incident energy plus about 5 MeV for the binding energy of this proton. The incident proton beam, at these energies, has a significant energy spread. Thus, with 100-MeV protons, the compound nucleus would have an excitation energy of from about 90 to 110 MeV, and with 70 MeV the range of excitation energies would be from about 60 to 80 MeV. At an excitation energy of 100 MeV, about 3% of the $In^{117}$ cases produced an $In^{111}$ product. The $In^{115}$ compound nucleus would have too much excitation energy to evaporate only four neutrons so that in no instance did the evaporation lead to an $In^{111}$ product. At an excitation energy of 70 MeV approximately 45% of the $In^{117}$ cases produced an $In^{111}$ product and about 5% of the $In^{115}$ cases led to $In^{111}$. Table III is a summary of these data and a comparison of the experimental estimate of the compound-nucleus contribution to the $(p, 4n)$ and $(p, 6n)$ cross sections at 70 and 100 MeV with the compound-nucleus cross section for these reactions based on Monte Carlo calculations. Considering the generally poor statistics available, the agreement appears to be quite good and at least is consistent with the hypothesis that these reactions have compound-nucleus contributions at low energies.

Presented in Fig. 7 is the excitation function for the $Cd^{111}$ $(p, n)$ $In^{111}$ and $Cd^{112}$ $(p, 2n)$ $In^{111}$ reactions from $\sim$4 to 400 MeV. The low-energy data are the results of Otozai *et al.*[16] These data form a smooth extension of the $(p, n)$ and $(p, 2n)$ excitation functions to lower energies. The low-energy peaks observed by Otozai *et al.* are due to compound-nucleus processes at these low energies. These peaks are very similar to that observed for the $Cd^{116}$ $(p, 6n)$ $In^{111}$ reaction below 150 MeV.

The point at 47 MeV for the $(p, 2n)$ reaction was an attempt to overlap the results of Otozai *et al.* with the high-energy results. The energy uncertainty of this point is about $\pm$10 MeV since this is about the minimum target radius for the Carnegie-Mellon University synchrocyclotron. The $Na^{24}/Na^{22}$ ratio from aluminum was determined at this radial setting to be $12\pm1$. Cumming[6] determined this ratio to be 12 at 47 MeV, which thus compares well with 50 MeV as the calculated value of the proton energy for this radial position.

The complete excitation functions up to 400 MeV, illustrated in Fig. 7, have maximum at 13 and 23 MeV for the $(p, n)$ and $(p, 2n)$ reactions, respectively. The Monte Carlo evaporation calculations, Fig. 6, indicate that the predicted maximum is from 10 to 20 MeV for the $Cd^{111}$ $(p, n)$ $In^{111}$ reaction and from 20 to 30 MeV for the $Cd^{112}$ $(p, 2n)$ $In^{111}$ reaction. Thus, the agreement with the experimental values is quite satisfactory.

## ACKNOWLEDGMENTS

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