Nuclear Structure Effects in (p, 2 nucleon) Reactions on the Separated Isotopes of Cadmium at 400 MeV* †

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The cross sections of $(p, 2p)$, (p, pn), and $(p, 2n)$ reactions at 400 MeV on the separated isotopes of cadmium were determined. The (p, pn) cross sections exhibit abrupt variations within a narrow target mass range. The data are examined in terms of the currently accepted mechanisms for high-energy (p, 2 nucleon) reactions. An estimate is made of the relative contribution of direct knockout processes versus the two-step inelastic scattering and neutron evaporation mechanism. There does not appear to be any obvious explanation for the abrupt cross-section variations. The cross section of the cadmium $(p, 2p)$ reactions is inversely proportional to the neutron skin thickness. This is consistent with the conclusion that these reactions take place predominantly by direct knockout processes and in the peripheral region of the nucleus.

INTRODUCTION

A large number of cross sections for the production of the so-called "simple" nuclear reactions, such as the $(p, 2n)$, (p, pn), and $(p, 2p)$, on a variety of target nuclei and at numerous incident proton energies above 100 MeV have been reported.[1,2] The majority of these studies were done using targets of monoisotopic stable elements, or elements with only a few stable isotopes. Most of the reported data, therefore, are for target isotopes located near the line of β stability. The purpose of this investigation and the one reported in the succeeding paper[3] was to systematically study the production, whenever possible, of (p, 2 nucleon) reactions from a target element having stable isotopes spanning a large change in mass number. In this paper are presented the results of the investigation of these reactions on the stable isotopes of cadmium, from ^{106}Cd to ^{114}Cd, and in the following paper the same kind of results are reported for the stable isotopes of tellurium for ^{122}Te to ^{130}Te.

The mechanisms of the simple high-energy nuclear reactions can be described by the Serber model.[4] According to this model, the interaction of incident particles with energies above about 100 MeV with nuclear matter takes place in two steps. The incident particle initiates a series of nucleon-nucleon collisions in which a number of nucleons are promptly ejected from the nucleus. This cascade of colliding nucleons continues until either all the collision partners are outside the nuclear potential or until one or more collision partners has less kinetic energy than their binding energy. The resulting excitation energy is then dissipated on a longer time scale by the statistical evaporations of neutrons, protons, and other heavier particles.

The production of (p, 2 nucleon) reactions, according to this model, requires severe limitations on the extent of both parts of the interaction. Clearly, the number of cascade nucleons cannot be in excess of two, and the number of evaporation nucleons cannot be in excess of one. The probability of compound nucleus formation and deexcitation at energies above 100 MeV is considered to be unlikely.[2] Thus, one path by which (p, pn) and $(p, 2p)$ reactions might take place would be by events in which the incident particle undergoes a small angle scattering, leaves the nucleus, and causes the ejection of one other nucleon. The excitation energy deposited from such a nucleon knockout would have to be less than about 10 MeV to prevent further nucleon evaporation.

An alternative path, which would also describe $(p, 2n)$ reactions, would involve events in which the incident proton made an inelastic scattering and imparted insufficient momentum to the collision nucleon to cause its prompt ejection. The excitation energy resulting from these events would have to be somewhat in excess of 10 MeV so that subsequent particle evaporation could take place.

The various kinds of proton-nucleon collisions which lead to (p, 2 nucleon) products can be symbolically represented by the following notation. Capital letters with tildes represent collision (cascade) partners to the left of the comma and represent ejected nucleons to the right of the comma. Thus, $(\tilde{P}\tilde{N}, \tilde{P}\tilde{N})$ represents a (p, pn) reaction taking place by a direct neutron knockout. Lower case letters, to the right of the comma represent evaporation nucleons. Thus $(\tilde{P}\tilde{P}, \tilde{P}n)$ represents a (p, p') scattering on a nuclear proton followed by neutron evaporation. The most likely types of nucleon-nucleon collisions for the three classes of (p, 2 nucleon) reactions are presented in Table I. Various types of less common multiple scatterings, excitation, and deexcitations are not included.

Mechanisms a and e have been referred to as knockout events, b, c, f, and g as inelastic scattering followed by nucleon evaporation, and d and h as charge-exchange scattering followed by nucleon evaporation. Note that mechanisms b and f involve inelastic p-p interactions while c and g involve inelastic p-n interactions. At incident energies in excess of 400-MeV (p, 2 nucleon) reactions can take place by paths involving meson production. The contribution of such paths is not considered to be important at the incident energy used in this study. Estimates of the relative contributions of the various mechanisms have been made by Remsberg[5] for the ^{65}Cu$(p,pn)^{64}$Cu reaction.

For a series of stable isotopes, such as ^{106}Cd to ^{114}Cd, both the neutron and proton binding energies exhibit systematic changes. It might be anticipated therefore that the contribution of these various mechanisms to (p, 2 nucleon) cross sections should also change. Furthermore, in this mass region $Z = 48$, N goes from 58 to 66, and thus the topmost neutron in the potential well may occupy a number of different quantum states. Since all these mechanisms, in order to avoid large excitation energies, require that the reaction takes place at the surface of the nucleus or in the nuclear skin region, the changing population of the topmost filled levels should affect the reaction cross section.

Most of the (p,pn) reaction cross sections reported at 400 MeV for targets of $A \geq 50$ are between 50 and 70 mb. However, as the population of nucleons within a band about 10 MeV deep from the top filled level changes, the (p, 2 nucleon) cross section should change. Such predictions were previously made by Grover[6] and Benioff,[7] the magnitudes of the effect calculated by Benioff, and at least partially substantiated by Porile and Tanaka.[8] Furthermore, Remsberg and Miller[9] have shown, that for targets with $A \sim 65$, the knockout mechanism (mechanism a) accounts for about 85% of the total cross section. Any variation in the (p,pn) cross sections from the cadmium isotopes, therefore, might be correlated with the number of neutron levels available, or with the dependence of the neutron skin thickness on target mass number, as suggested by Karol and Miller.[10]

TABLE I. Possible mechanisms of high-energy (p, 2 nucleon) reactions.

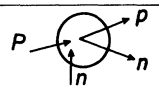
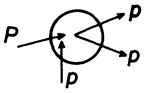
Symbolic representation	Diagram (p,pn)	Description
a $(\tilde{P}\tilde{N}, \tilde{P}\tilde{N})$		Knockout
b $(\tilde{P}\tilde{P}, \tilde{P}'n)$		Inelastic (p,p) scattering followed by neutron evaporation
c $(\tilde{P}\tilde{N}, \tilde{P}'n)$		Inelastic p-n scattering followed by neutron evaporation
d $(\tilde{P}\tilde{N}, \tilde{N}p)$		Charge-exchange scattering followed by proton evaporation
	($p,2p$)	
e $(\tilde{P}\tilde{P}, \tilde{P}\tilde{P})$		Knockout
f $(\tilde{P}\tilde{P}, P'p)$		Inelastic p-p scattering followed by proton evaporation
g $(\tilde{P}\tilde{N}, \tilde{P}'p)$		Inelastic p-n scattering followed by proton evaporation
	($p,2n$)	
h $(\tilde{P}\tilde{N}, \tilde{N}n)$		Charge-exchange scattering followed by neutron evaporation

TABLE II. Target materials. Composition of separated isotopes as received from Oak Ridge National Laboratory (given in %). For example, the Cd-106 target mixture had a composition 88.6% in ^{106}Cd. Refer to text for use of symbol Cd-N.

Isotope	Target compositions (Cd-N)							
	^{106}Cd	^{108}Cd	^{110}Cd	^{111}Cd	^{112}Cd	^{113}Cd	^{114}Cd	^{116}Cd
^{106}Cd	88.6	0.43	1.99	1.62	2.72	1.18	2.51	0.99
^{108}Cd	0.52	81.6	5.37	3.15	3.85	1.59	3.14	0.74
^{110}Cd	<0.01	<0.01	97.2	1.04	0.90	0.27	0.49	0.09
^{112}Cd	<0.02	<0.02	0.13	0.35	98.5	0.44	0.55	0.07
^{113}Cd	<0.01	<0.01	0.15	0.26	1.01	96.3	2.13	0.15
^{114}Cd	<0.01	<0.01	0.07	0.09	0.26	0.33	99.1	0.07

EXPERIMENTAL

Targets were bombarded in the internal proton beam of the Carnegie-Mellon University synchrocyclotron at 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 this energy. Irradiations were of 5- to 30-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 isotope and aluminum powder into a plastic capsule and shaking the mixture with a plastic ball on a "Wig-l-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 II.

After irradiation the targets were dissolved in the presence of appropriate carriers and chemically purified using adaptations of standard radiochemical procedures.[11] Chemical yields were determined gravimetrically as follows: silver as silver chloride, cadmium as the salt of anthranilic acid, and indium as the complex 8-hydroxyquinoline.

In all cases, cross sections were measured relative to the cross section of the ^{27}Al(p, $3pn$)^{24}Na monitor reaction, using a value of 10.5 mb as suggested by Cumming.[12] The targets were composed of 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 ±3%, and this agreement was considered as evidence for the proper alignment of the target.

Disintegration properties of the product nuclides studied were taken from the *Nuclear Data Sheets*[13] and in the case of ^{105}Ag from Suter *et al.*[14] The

TABLE III. Decay schematics. All properties except where noted were taken from *Nuclear Data Sheets*. See Ref. 13.

Nuclide	Half-life	Mode of decay	Maximum energy (MeV)	Branching abundance
^{105}Ag	40 day	x ray	0.021	1.00
^{105}Cd	55 min	counted ^{105}Ag		
^{107}Cd	6.5 h	x ray	0.022	1.00 [a] $e_K/\gamma = 10 \pm 0.5$ $K/L+M = 0.88$
^{107}In	31.5 min	counted ^{107}Cd		
^{109}Cd	470 day	x ray	0.022	1.00 [b] $e_K/\gamma = 11.0 \pm 0.3$ $K/L+M = 0.805$
^{109}In	4.3 h	counted ^{109}Cd		
^{111}Ag	7.5 day	β^-	1.05, 0.71	1.00
^{111}In	2.8 day	γ	0.247, 0.173	1.00 [a] $e/\gamma = 0.064$
^{112}Ag	3.2 h	β^-	4.05	1.00
^{113}Ag	5.3 h	β^-	2.00	1.00

[a] D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. 30, 585 (1958).
[b] See Ref. 14.

specific disintegration observed for each product nuclide studied is listed in Table III. Radiations were detected with an end-window gas-flow β-proportional counter, a $\frac{1}{32}$-in.$\times 1\frac{1}{2}$-in. NaI x-ray crystal and 3-in.$\times$3-in. NaI(Tl) crystal. Both crystals were connected via a photomultiplier tube to a multichannel analyzer. Stability of the proportional system was within 3% over the period in which measurements were made. The β detector and associated electronics were calibrated by counting standardized sources as described by Bayhurst and Prestwood.[15] The x-ray crystal was calibrated for ^{109}Cd and ^{107}Cd by counting a standardized ^{109}Cd source supplied by Chem Trac Division of Baird-Atomic, Inc. The x-ray crystal was calibrated by counting the γ rays in the energy region from 280 to 344 keV. Suter *et al.*[14] have calculated that γ rays account for 69% of the ^{105}Ag disintegration. Heath's[16] values were used to calibrate the 3-in. crystal.

A least-squares analysis of all the decay curves was performed with the aid of a digital computer.

Since it was not possible to obtain isotopes enriched to 100%, it was necessary to correct for the contamination of other isotopes present in a sample. This correction was accomplished by solving simultaneous equations of the following form: $(\sum_M P_M{}^N \sigma_M) = \sigma_N$, where σ_N is the observed cross section from mixture Cd-N, σ_M is the true cross section from isotope ^{M}Cd, and $P_M{}^N$ is the percent of isotope ^{M}Cd in mixture Cd-N. The symbols M and N each take the values 106, 108, 110 through 114, and 116. The error in the true cross section, σ_M, due to the contamination of other isotopes was thus reduced to less than 1%.

RESULTS

The experimentally determined (p, 2 nucleon) reaction cross sections are presented in Table IV. The uncertainties listed are the rms deviations from the average for identical determinations. 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, and about ±3% for chemical yield determination. The uncertainties in the calibrations of the radiation detectors were as follows: ±10% for the β-proportional counter; for the x-ray crystal, ±11% for ^{109}Cd and ±15% for ^{107}Cd; and ±5% for the 3-in. NaI crystal. The over-all uncertainty, taken to be the geometric mean of the individual uncertainties, varied for each system because of the different decay properties of the nuclides. Therefore this uncertainty is listed separately in Table IV for each product studied.

The (p, 2 nucleon) reaction might be expected to be sensitive to secondary protons since (p, $2n$) and (p, pn) reactions have larger cross sections at lower energies. A thickness study by Church[17] on the ^{90}Zr(p, $2n$)^{89}Nb system using pellets similar to those used in this study showed that for surface densities from 20 to 220 mg/cm^2 there was no measurable effect due to secondaries. Also, an investigation of the effect of secondaries on the ^{12}C(p, pn)^{11}C reaction showed no measurable change in cross section for target surface densities from 10 to 150 mg/cm^2.[11] Since there are no data for these reactions for target thicknesses less than 10 mg/cm^2, no corrections were applied to the data for the target thicknesses used in this study.

Using enriched targets of ^{106}Cd, Dwyer[18] reports a cross section for the ^{106}Cd(p, pn)^{105}Cd reaction at 400 MeV of 5.4 ± 2.2 and 7.0 ± 2.8 mb for the ^{106}Cd-(p, $2p$)^{105}Ag reaction at the same energy. These values are factors of 6 and 3, respectively, lower than the values reported here. There is no apparent reason for this discrepancy.

DISCUSSION

A. (p, pn) Reactions

The cross sections of (p, pn) reactions for proton energies at or near 400 MeV and for systems of two or more target nuclides having the same atomic number are illustrated in Fig. 1. The gross feature of the cross sections of all known (p, pn) reactions versus target mass number has been discussed previously.[2,3,9,10] For targets of mass about equal to or greater than 60, the cross section is roughly constant between about 50 and 70 mb with the exception of some of the data being reported in this paper. However, for $A \sim 60$ there are several cases in which the cross section changes abruptly within a change in target mass of only a few nucleons. For example, the (p, pn) cross section for ^{54}Fe is 36.6 ± 1.2 mb, and for ^{56}Fe it is 63.9 ± 3.8 mb. Excluding the cadmium data reported here, and the tellurium data reported in the subsequent paper, there are several

TABLE IV. Experimental cross sections at 400 MeV in mb. The numbers in parentheses represent the over-all uncertainty (%).

Target	Reaction (p, $2n$)	(p, pn)	(p, $2p$)
^{106}Cd		30.4 ± 0.9 (15)	21.0 ± 2.0 (15)
^{108}Cd	6.25 ± 0.84 (22)	101.7 ± 12.8 (19)	
^{110}Cd	3.58 ± 0.54 (15)	44.8 ± 4.7	
^{111}Cd			
^{112}Cd	4.06 ± 0.07 (12)		16.2 ± 0.4 (15)
^{113}Cd			14.2 ± 0.3 (17)
^{114}Cd			13.7 ± 0.1 (16)

other cases which exhibit fairly abrupt cross-section differences when a comparison is made of targets of separated isotopes of a given element. These cases are connected by dashed lines in Fig. 1. Also included in Fig. 1 are data in the mass region 81–89 which again illustrate an abrupt change in $\sigma(p, pn)$, outside the 50–70-mb range, even though Z is not constant.

It is difficult to understand how any of the currently proposed mechanisms of (p, 2 nucleon) reactions can explain these abrupt cross-section differences. If the explanation of this effect is sought within the framework of the currently proposed mechanisms of these reactions it becomes necessary to consider: (a) abrupt changes, within a few mass numbers, of the relative contribution of the various mechanisms, particularly a change in the ($\tilde{P}, \tilde{P}\tilde{N}$) versus ($\tilde{P}, \tilde{P}'n$);[19] (b) in terms of the knockout mechanism, abrupt changes in the number of available target neutrons within the peripheral nuclear region could provide an explanation, and related to this; (c) changes in the neutron skin thickness as a function of neutron number could account for at least part of the observed effects. The variation of the cadmium (p, pn) cross sections with mass number will be examined in terms of these three possible explanations.

(i) Change in contribution of various mechanisms. The procedure employed by Remsberg and Miller[9] provides a means of estimating the relative contributions of mechanism a, ($\tilde{P}, \tilde{P}\tilde{N}$) versus mechanisms b, c, and d, ($\tilde{P}, \tilde{P}n$). The procedure requires knowledge of both the (p, pn) and ($p, 2n$) reaction cross section for the same target isotope. Both of these measurements were made for ^{108}Cd and ^{110}Cd. The ratio of $\sigma(p, p'x)/\sigma(\tilde{P}, \tilde{N}x)$ is calculated where x represents either neutron or proton evaporation following either p-p or p-n interactions of the incident particle. This ratio was calculated using the same expression as Remsberg and Miller and assuming the term $W(\Theta)$ was constant over the range of angles of interest. This term, $W(\Theta)$, is the probability that a collision with a c.m. scattering angle Θ results in an energy transfer consistent with the evaporation of one nucleon. This ratio was found to be 1.54 for ^{108}Cd and 1.52 for ^{110}Cd. By means of evaporation calculations,[20] the ratio, G_p/G_n, of the probability of one and only one-proton evaporation to one and only one-neutron evaporation was obtained for ^{108}In and ^{110}In. Both these values were about 0.1. Using these values a total $\sigma(p, p'x)$ of about 10.6 mb for ^{108}Cd and 6.0 mb for ^{110}Cd were obtained. The number of ($\tilde{P}, \tilde{P}'n$) events can then be obtained by multiplying this total by the probability of one-neutron evaporation. This yielded a value of 9.6 mb for $\sigma(\tilde{P}, \tilde{P}'n)$ for ^{108}Cd and 5.4 mb for the same quantity for ^{110}Cd. The abrupt change in total $\sigma(p, pn)$ for these two targets obviously can not be explained by a change in the relative contributions of the two mechanisms considered. It is interesting to note, however, that the fraction of the total $\sigma(p, pn)$ estimated by $\sigma(\tilde{P}, \tilde{P}'n)$ events is about the same for the two targets: 9.4% for ^{108}Cd and 12% for ^{110}Cd. Within the rather large uncertainties of these estimates, about ±25% of the values given, these fractions are in agreement with the 15% estimate of ($\tilde{P}, \tilde{P}'n$) made by Remsberg and Miller for ^{52}Cr and ^{56}Fe at 370 MeV.

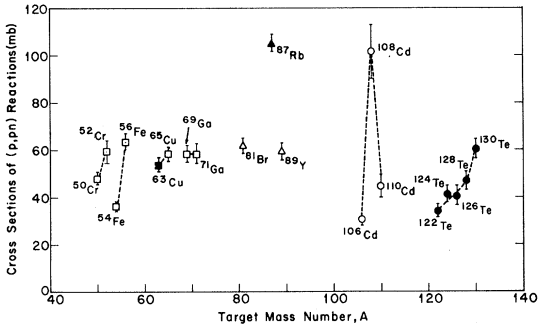


FIG. 1. Cross sections of (p, pn) reactions for target nuclides having the same atomic number, versus target mass number between 350–450 MeV. ○ this work; ● Ref. 3; □ Ref. 9; ■ see, S. S. Markowitz, F. S. Rowland, and G. Friedlander, Phys. Rev. 112, 1295 (1958). Also illustrated are known values of $\sigma(p, pn)$ for A between 81 and 89, △ Ref. 23; ▲ Ref. 21.

(ii) Variation in the number of neutrons available for ($\tilde{P}, \tilde{P}\tilde{N}$) events. Porile and Tanaka[8] were able to demonstrate a correlation for the magnitude of the (p, pn) cross sections for targets having neutron numbers between 36 and 46, produced with 2.9-GeV protons, with the number of available neutrons for ($\tilde{P}, \tilde{P}\tilde{N}$) events. However, in the region of ^{106}Cd to ^{110}Cd, according to the shell model, neutrons are filling the $2d_{5/2}$ level. It is difficult to see how the addition of two or four neutrons to ^{106}Cd could cause the energies of the levels of the available neutrons to shift enough to alter significantly the value of the hole energies resulting from ($\tilde{P}, \tilde{P}\tilde{N}$) knockout events. The hole energy may be defined as the difference in the binding energy of the neutron which was removed to the binding energy of the least-bound neutron. In the region ^{106}Cd to ^{112}Cd, the number of available neutrons, the number of neutrons in levels sufficiently high that the removal of one of them does not produce an excitation energy sufficient to cause particle evaporation, does not appear to change in any way consistent with the abrupt change in cross section. Furthermore, the neutron binding energies of the (p, pn) product nuclei decrease in a regular fashion with increasing neutron number. Thus, unless a particularly unexpected variation of the neutron

level positions is present, there appears to be no direct connection of the values of (p, pn) cross sections with the number of available neutrons.

(iii) Variation of neutron skin thickness. As pointed out by Karol and Miller,[10] the variation of the neutron skin thickness could effect the magnitude of nuclear reactions which must take place predominately in this peripheral region. The neutron skin thickness t, equal to the difference between R_n and R_z the radii of spheres corresponding to the neutron and proton density distributions, can be estimated by the expressions given by Myers.[21] In Table V are presented values of t, in fermis, for the nuclides ^{106}Cd to ^{114}Cd. One might predict that the (p, pn) cross section should vary, at least roughly, with the increase in value of the skin thickness. This is clearly not the case. However if a comparison is made of ^{106}Cd with ^{110}Cd, a reasonable correlation is observed. The ratio of $t(^{110}\text{Cd})/t(^{106}\text{Cd})$ is 1.44 while the corresponding cross-section ratio, $\sigma^{110}\text{Cd}(p, pn)/\sigma^{106}\text{Cd}(p, pn)$ is 1.38. This implies that the ^{108}Cd(p, pn) cross section is anomously high.

Two comments can be made relative to the high value of the ^{108}Cd(p, pn) reaction cross section. One argument against this cross section being in error is that the ^{107}Cd and ^{109}Cd decay schemes are essentially identical. Furthermore, the detectors were calibrated with standardized ^{109}Cd sources. All the other aspects of the experiment were identical. Of course other unknown sources of experimental error might be present. However, other high values of (p, pn) reaction cross sections have been observed. For example, Kiefer[22] reports a value for the ^{87}Rb$(p, pn)^{86}$Rb reaction of over 100 mb at 350 MeV as contrasted with a value of 61.9 for ^{81}Br and 59.6 mb for ^{89}Y, each at 400 MeV.[23] The reason for the high cross section of ^{108}Cd is unexplainable at this time.

TABLE V. Cadmium isotope neutron skin thickness (calculated according to Ref. 21).

Isotope	Neutron skin thickness, t (fm)
^{106}Cd	0.114
^{107}Cd	0.127
^{108}Cd	0.140
^{109}Cd	0.152
^{110}Cd	0.164
^{111}Cd	0.176
^{112}Cd	0.188
^{113}Cd	0.199
^{114}Cd	0.211

B. $(p, 2p)$ Reactions

The predominant mechanism for $(p, 2p)$ reactions is probably $(\tilde{P}, \tilde{P}\tilde{P})$, mechanism e. Mechanisms f and g describe inelastic scattering events followed by proton evaporations. The probability of proton evaporation from nuclides in the vicinity of cadmium is small because of the relatively high coulomb barrier. As can be seen from Table V, the neutron skin thickness increases with increasing neutron number for constant Z. Since $(p, 2p)$ reactions also must involve collisions in the peripheral region of the nucleus,[6,7] and if the neutron density increases in this region as neutrons are added, holding Z constant, then it might be expected that the probability of $(p, 2p)$ reactions should decrease with increasing neutron number. Figure 2 is a plot of the cross section of the Cd$(p, 2p)$ reactions versus the neutron skin thickness. The decreasing dependence of the data with neutron skin thickness is consistent with this argument.

C. $(p, 2n)$ Reactions

The cross sections of the three $(p, 2n)$ reactions measured in this study will be discussed, together with the results of the $(p, 2n)$ reactions, on the separated isotopes of tellurium in the succeeding paper.

CONCLUSION

It can be concluded that the $(p, 2$ nucleon) reaction cross sections reported here, are consistent in a general way, with the knockout mechanism and are strongly dependent on the neutron skin thickness and the nucleon composition of this peripheral region. No simple conclusion can be made, however, of the anomously high values and abrupt changes observed for some of the values. It may be that no one explanation will suffice. Also,

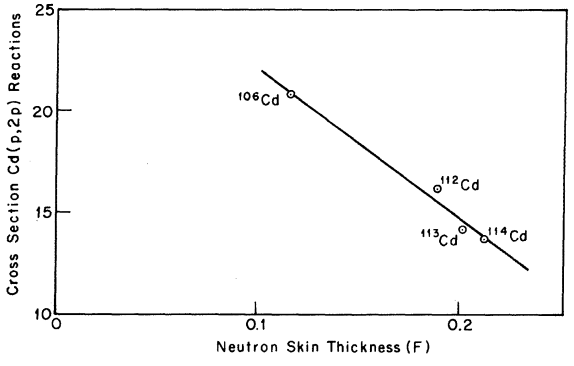


FIG. 2. Dependence of the cadmium $(p, 2p)$ cross section on neutron skin thickness.

it should be kept in mind, that the various mechanisms that have been suggested are at best crude representations for a process which must be very sensitive to the nucleon configuration in the nuclear surface region. The appropriate quantal calculations might provide some insight.

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[19]The notation used here, and subsequently, differs from Table I in that the nature of the collision nucleon is ignored. Here, $(\tilde{P}, \tilde{P}\tilde{N})$ represents a cascade ejection of a proton and neutron. Lower-case letters represent evaporation nucleons following the cascade event.

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