results presented here for 0.72-Bev protons. The agreement at these energies has also been observed for other types of measurement.[22,34]

Thus, the failure to include the correct density distribution of nucleons in the surface appears to affect only the (p,pn) cross section at the lower energies to any marked extent. We should expect the nucleon-nucleon collisions that are involved in more complicated reactions to occur closer to the center of the nucleus, on the average. Hence, the character of the nuclear surface should affect the cascade phase of the calculation for (p,pxn) and $(p,2pxn)$ reactions to a progressively smaller extent as the value of x increases. Because of experimental uncertainty it is not possible to assess the role of the nuclear surface in the $(p,p2n)$ reaction from these measurements. However, it does appear that this reaction is much less sensitive to the nature of the nuclear surface than is the (p,pn) reaction.

At 2 Bev there is essentially no agreement between the calculated and the experimental values. Work of a similar nature on indium confirms this lack of agreement at 2 Bev.[2] Comparisons have been made of the measured and calculated sum of the cross sections to produce all nuclides of a given mass number for 340-Mev protons and for 2.2- and 5.7-Bev protons incident on copper.[14,22] As in the work reported here, good agreement was obtained at the lower energy. Barr, however, found that calculated values are too small by a factor of roughly 2 to 3 at the higher energies for products with masses near that of the target.[14] The reason for the disagreement of the experimental and calculated values at 2 Bev compared to the fairly good agreement at lower energies, except for the (p,pn) reaction, is not clear. It may be that inclusion of a proper description of the nuclear surface in the calculation will rectify the comparison. This seems to be the case for the (p,pn) reaction at incident proton energies in the multi-Bev range.[31] A discussion of this and other possibilities is deferred to the following paper in which further pertinent evidence is presented.[2]

[34] E. T. Hunter and J. M. Miller, Phys. Rev. **115**, 1053 (1959).

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Interaction of High-Energy Protons with Indium*

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Indium was bombarded with protons ranging in energy from 1.0 to 6.2 Bev. Reactions of the type (p,pxn), $(p,2pxn)$, (p,p'), and $(p,p\pi^+)$ that produce isotopes of indium and cadmium were investigated. The excitation functions are constant within experimental error in this energy region with possible exceptions for Cd^{115} and In^{115m} at 1.0 Bev. These results are compared with two types of calculation. In one treatment, the nucleus is considered to be a degenerate Fermi gas of nucleons. The cross sections that were calculated with this nuclear model at 2 Bev are much smaller than the experimental values. There is good agreement at 1 Bev for nuclides with mass number less than 113. The second treatment takes into account the shell structure of In^{115}. The latter calculation for the (p,pn) reaction was in good agreement with the experimental results at 4.1 and 6.2 Bev. The comparison of the experimental results with the calculated values is discussed in terms of the adequacy of the calculations.

INDIUM is favorable for studying reactions that cause relatively little change in the target nucleus. Both of its stable isotopes have isomeric states that permit investigation of the (p,p') reaction by radiochemical methods. The decay characteristics of the neighboring radioactive nuclides, including the occurrence of isomerism, are suitable for the study of other types of nuclear reactions. In the work reported here, indium was bombarded with protons accelerated by the Bevatron to energies of 1.0, 2.0, 4.1, and 6.2 Bev. The cross sections for the formation of indium and cadmium isotopes and Be^7 were measured. The latter is of interest because it is one of the lightest nuclides that can be measured by radiochemical techniques.

As in the preceding paper on iodine,[1] the experimental results are discussed in terms of the initial interaction

* This work was performed under the auspices of the U. S. Atomic Energy Commission.

[1] I. M. Ladenbauer and L. Winsberg, preceding paper [Phys. Rev. **119**, 1368 (1960)].

and the subsequent processes that cause the escape of a few more particles. The (p,pn) reaction reported here has also been treated by Benioff.[2] The result for the formation of Be^7 is compared to similar studies with other targets.

EXPERIMENTAL PROCEDURE[3]

The target assembly consisted of a 0.003-in. indium target foil and a 0.003-in. aluminum monitor foil. Three 0.001-in. aluminum guard foils were used to separate and cover the foils as a protection from recoil and secondary particles. The five foils (each 2 by $\frac{3}{4}$ in.) were stacked together and held in a Lucite target holder so that the edges were aligned as closely as possible. After the bombardment, the outer 1 in. of the foil stack was cut off and used for radiochemical analysis. Additional bombardments were performed in which the thickness of the indium foil was varied in order to estimate the extent of reactions produced by secondary particles.

The 0.003-in. indium foil (>99.9% indium) was obtained from the Indium Corporation of America. Spectroscopic analysis of the indium showed the presence of 0.01% tin and zinc, 0.006% lead, and 0.002% copper. Typical detection limits for other elements were <0.1% thallium and iron, <0.05% cadmium and tungsten, and <0.005% bismuth.

The incident proton beam was monitored by means of the $Al^{27}(p,3pn)Na^{24}$ reaction. The cross section for this reaction was taken as 10.5 mb for protons in the energy range of 1 to 6 Bev.[4] The error in this value is believed to be less than 10%. The beta radiation of the Na^{24} was counted directly in the aluminum foil without chemical separation.

After bombardment the indium foil was weighed and then dissolved in a solution of HCl and HNO_3 containing 10- to 20-mg quantities of beryllium and cadmium as carriers. The beryllium, cadmium, and indium fractions were separated and purified by standard radiochemical procedures.[5,6]

An end-window, gas-flow proportional counter was used to count beta particles and conversion electrons. The counting rate of a Na^{24} source in the proportional counter was compared with its absolute disintegration rate obtained by the coincidence counting technique. The comparison factor obtained in this manner was used to calculate the disintegration rates of those nuclides emitting energetic (>1-Mev) beta particles. In the case of those nuclides emitting only lower energy particles, it was necessary to apply individual corrections for backscattering, air and window absorption, self-scattering and self-absorption, and geometry.[7–10]

A gamma-ray scintillation pulse-height analyzer (50 and 100 channels) with a thallium-activated NaI crystal (1 in. by $1\frac{1}{2}$ in. diam) was used to count the gamma rays of particular energies. The variation of counting efficiency with gamma-ray energy was taken from the data of Kalkstein and Hollander.[11] The geometry calibration was obtained with standardized Na^{24} and Am^{241} sources.

In order to provide a means for comparing results presented here with those obtained elsewhere, we list the number of particles or photons emitted per disintegration in Table I for each nuclide measured.[12]

RESULTS

The measured values of the cross sections are presented in Table II as a function of proton energy and target thickness. Standard deviations are given in those cases where duplicate determinations were made. It is estimated that the over-all uncertainty in the cross sections due to errors in counting efficiencies, beta-counting correction factors, chemical yields, counting statistics, monitor cross section, etc., is about ±30%. The cross sections for the nuclides Cd^{107}, Cd^{109}, and In^{109} are less accurately known than the others because of uncertainties in the counting corrections. The low counting rates of Be^7 and Cd^{115m} did not permit the accurate measurement of these nuclides.

The yield listed for Cd^{109} has been corrected for the decay of In^{109}. All other cross sections except those for Be^7, In^{109}, and possibly Cd^{107} and In^{111} represent inde-

TABLE I. Number of particles and photons emitted per disintegration.

Nuclide	Half-life	Type of radiation	Energy (Mev)	Particles or photons per disintegration
Be^7	53 days	γ	0.478	0.12
Cd^{107}	6.7 hr	e^-	0.090, 0.068	0.94
Cd^{109}	470 days	e^-	0.084, 0.062	0.91
Cd^{115}	53 hr	β^-	1.11, 0.85. 0.60	1.00
Cd^{115m}	43 days	β^-	1.16, 0.67	1.00
In^{109}	4.3 hr	γ	0.205	~0.7
In^{110m}	5.0 hr	γ	0.66	1.00
In^{111}	2.84 days	γ	0.172, 0.247	0.89, 0.94
In^{113m}	104 min	γ	0.393	0.65
In^{114m}	49 days	β^-	1.98	0.95
		γ	0.191	0.18
In^{115m}	4.50 hr	γ	0.335	0.48

[2] P. A. Benioff, Phys. Rev. **119**, 316 (1960).
[3] For details see D. R. Nethaway, University of California Radiation Laboratory Report UCRL-3628, January, 1957 (unpublished).
[4] P. A. Benioff, Phys. Rev. **119**, 316 (1960).
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[7] B. P. Burtt, Nucleonics **5**, No. 2, 28 (1949).
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[10] L. R. Zumwalt, Atomic Energy Commission Report AECU-567, September, 1949 (unpublished).
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[12] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

TABLE II. Measured values for cross sections.

Proton energy	1.0 Bev	2.0 Bev	4.1 Bev	6.2 Bev		
Target thickness	37 mg/cm²	97 mg/cm²	97 mg/cm²	26 mg/cm²	97 mg/cm²	476 mg/cm²
Nuclide	Cross sections (millibarns)					
Be^{7}					14.1±0.4	
Cd^{107}	26	32	26±2	27	29±3	27
Cd^{109}	35	51±2	44±3	45	52±6	74
Cd^{115}	0.03	0.06±0.01	0.066±0.001	0.05	0.071±0.004	0.13
Cd^{115m}	0.13	0.145±0.001	0.15±0.02	0.06	0.147±0.006	0.24
In^{109}	10	11				
In^{110m}	12	17				
In^{111}	16	21		17		26
In^{113m}	1.9	2.5				
In^{114m}	42	49±1	57±1	57	61±9	70
In^{115m}	1.7	4.1±0.6	5.0		4.2±0.6	

pendent yields. Since the products Cd^{115}, Cd^{115m}, In^{114m}, and In^{115m} are formed exclusively from In^{115}, the cross sections reported here have been corrected for the isotopic abundance of In^{115}(0.958). The remainder of the products can be formed from both In^{113} and In^{115}.

In order to estimate how much of the yield was due to impurities in the target foil, a determination of the yield of Cd^{117} was made. This nuclide can be formed from In^{115} only by an extremely unlikely reaction, so that any found should be an indication of higher-Z impurities in the indium. The Cd^{117} was measured by separating and counting the radiations from the In^{117} daughter. The cross section obtained by this method is 0.007 mb or less. Because this is a small value, we will disregard the presence of impurities.

The particles that result from the interaction of protons with the target assembly may cause further reactions of a secondary nature. The production of Cd^{115} and Cd^{115m} should be especially sensitive to the presence of neutrons, since these isotopes can result from (n,p) reactions as well as from the $(p,p\pi^{+})$ reaction induced by incident protons. Furthermore, the cross section of the latter reaction is small. The variation of cross section for the formation of Cd^{115} at 6.2 Bev as a function of the target thickness indicates a possible 25% contribution from secondary particles for the thinner targets (Table II). A similar effect is undoubtedly present at the lower bombarding energies. Fung and Turkevich studied the $Cu^{65}(p,p\pi^{+})Ni^{65}$ reaction with copper targets having a thickness of 23.9 mg/cm². At 440 Mev their results indicated a possible 7% contribution to the cross section from secondary reactions.[13] The variation in the cross section of Cd^{115m} is not a good test of this effect because of the relatively small radioactivity of this isomer. A smaller variation of measured cross section with target thickness is observed in the case of the other isotopes at 6.2 Bev.

[13] S. C. Fung and A. Turkevich, Phys. Rev. **95**, 176 (1954).

DISCUSSION

A prominent feature of these results is the constancy, within experimental error, of the measured cross sections between 2.0 and 6.2 Bev, shown in Table II. We, therefore, expect the cross sections for the formation of indium isotopes at 2.0 Bev to be characteristic of the (p,pxn) reactions in this energy range (Fig. 1 and Table II). Presumably, this is also true for the cadmium isotopes, including those not detected. In the case of the Cd^{115} isomers, the ratio of isomer yields, as well as the total cross section for this isotope, is constant at these energies. There may be a deviation from constancy in the values of the cross sections at 1.0 Bev, especially for Cd^{115} and In^{115m} (Fig. 1 and Table II). In most cases this deviation is smaller than the experimental error. These observations and the actual values of the cross sections will be considered in terms of the mechanism of these reactions.

It is customary to assume that the collision of a high-energy nucleon with a nucleon inside a nucleus is identical with a collision between free nucleons at the same energy in the center of mass, with one restriction only: After the collision neither particle can be left in a state already occupied by a like particle. This assumption is basic to the two types of calculation that have been

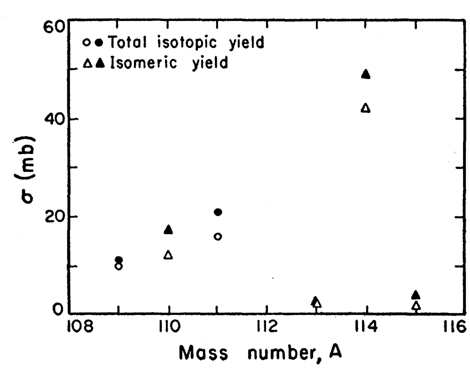

FIG. 1. Cross sections for the formation of indium isotopes at 1.0 Bev (open circles and triangles) and at 2.0 Bev (closed circles and triangles).

made for high-energy reactions. In one treatment, the nucleus is considered to be a degenerate Fermi gas of nucleons and to have a constant nuclear density.[14] The second type of calculation takes into account the specific shell structure of the target nucleus and the diffuse nature of the nuclear surface. Benioff's calculations of the second type[2] have been directly applied only to the reactions that leave the target nucleus relatively undamaged, e.g., the (p,pn) case reported here. The results shown in Table II and Fig. 1 will be analyzed in terms of these two nuclear models.

A. Comparison Based on Fermi-Gas Model with Constant Nuclear Density

The calculations based on the Fermi-gas model are divided into two parts: (a) an initial prompt-cascade process, which results in an excited residual nucleus, and (b) the ensuing de-excitation by evaporation of light particles. The former calculation was actually made for the target nuclei, Ru^{100} and Ce^{140} with a radius parameter of 1.3×10^{-13} cm.[14] The nuclear density was taken to be constant throughout the nucleus. From these results at 1 Bev (Ru^{100} only) and at 2 Bev, the corresponding residual nuclei for the target In^{115} were obtained, as described in the preceding paper for I^{127}.[1] Fraenkel made the evaporation calculation on the Weizmann Institute computer[15–17] with a radius parameter of 1.7×10^{-13} cm and a level-density parameter of $A/10$. Pairing and shell corrections were made. The radius parameter used in the latter calculation is different from that used for the cascade stage. The yield of neutrons and charged particles in the evaporation stage is relatively insensitive to changes in this parameter. The distribution of nuclei and their energies of excitation resulting from the cascade process were calculated for 654 events induced by protons incident on Ru^{100} at 1 Bev, and for 550 events with Ru^{100} and 563 events with Ce^{140} at 2 Bev. Complete evaporation calculations were repeated ten times for each inelastic event. (In approximately 5% of the cases, the protons were calculated to pass through the nucleus without any interaction.) The ratios of the calculated to experimental results are given in Table III. The values for the (p,pxn) reactions are also plotted in Fig. 5 of the preceding article[1] as solid triangles for ratios based on Ru^{100} and as open triangles for ratios based on Ce^{140}. Each point indicated by an arrow directed downward represents an upper limit because the experimental result is for only one of the isomers.

The ratios for indium as a target are in general agreement with those for iodine at the same energy of the incident proton.[1] The calculated results for both iodine and indium are in better agreement with the experimental values at 1 Bev than at 2 Bev. The comparison at 1 Bev for several isotopes of indium is ambiguous, however, because of unmeasured isomers. Although the ratios for In^{109} and Cd^{109} are each far from 1.0 at this energy, the value for the sum of the calculated cross sections of the two nuclides divided by the sum of the experimental results is fairly close to unity. From this point of view, the agreement at 1 Bev is quite good for nuclides with mass number smaller than 113.

All of the calculated cross sections at 2 Bev, with the possible exception of the (p,p') calculation based on Ce^{140}, are much smaller than the measured values. This lack of agreement is also observed at this energy for iodine.[1] In view of our ability to measure only the excited state of In^{115}, the ratio for (p,p') based on Ce^{140} is only an upper limit and, therefore, may not represent an exception. The other cases, in which only upper limits were measured for similar reasons, are the isotopes of indium with masses 110, 113, and 114.

The value of the cross section for the formation of In^{110m} appears to be in line with the values for In^{109} and In^{111} (see Table II and Fig. 1). Measurements of pion-induced reactions in iodine yielding radioactive indium isotopes indicate that the high-spin isomers are formed with much larger cross sections than the corresponding isomers with low spin.[18] From this we conclude that In^{110m} has a higher spin than does the ground state, in agreement with the known spins of isomers of other even-A isotopes of indium. According to this line of reasoning, we might expect the cross section for the formation of In^{114m} to be nearly equal in value to the total isotopic cross section. The indium isomers with mass numbers 113 and 115 have a low spin (1/2) relative to that of the ground state (9/2). We therefore conclude

TABLE III. Ratios of calculated to experimental cross sections for the reactions $In^{115}(p,pxn)In^{115-x}$, $In^{115}(p,2pxn)Cd^{114-x}$, and $In^{115}(p,p\pi^+)Cd^{115}$ for 1-Bev and 2-Bev protons.

Reaction[a]	Product detected	$\sigma_{calc}/\sigma_{exp}$ 1 Bev Ru^{100} [b]	2 Bev Ru^{100} [b]	2 Bev Ce^{140} [b]
(p,p')	In^{115m}	0	<0.17	<1.09
(p,pn)	In^{114m}	$\lesssim0.33$[c]	$\lesssim0.01$[c]	$\lesssim0.10$[c]
$(p,p2n)$	In^{113m}	<8.1	<0.27	<0.18
$(p,p4n)$	In^{111}	0.95	0.25	0.10
$(p,p5n)$	In^{110m}	$\lesssim1.1$[c]	$\lesssim0.04$[c]	$\lesssim0.18$[c]
$(p,p6n)$	In^{109}	1.8	0.06	0.12
$(p,p\pi^+)$	Cd^{115}	0[d]	0[d]	0[d]
$(p,2p5n)$	Cd^{109}	0.33	0.01	0.14
$(p,2p7n)$	Cd^{107}	0.67	0.21	0.14

[a] The symbols inside the parentheses indicate one of the possible reactions to produce the given product.
[b] The cascade calculation was made for the targets Ru^{100} and Ce^{140} and from these results the corresponding products for the target indium were obtained.
[c] The experimental result is for the high-spin isomer and is probably close to that for the isotope (see text and Fig. 1).
[d] No $(p,p\pi^+)$ cases from calculation. One calculated case corresponds to 0.2 mb.

[14] N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. M. Miller, and G. Friedlander, Phys. Rev. **110**, 185, 204 (1958).
[15] I. Dostrovsky, P. Rabinowitz, and R. Bivins, Phys. Rev. **111**, 1659 (1958).
[16] I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. **116**, 683 (1959).
[17] I. Dostrovsky, Z. Fraenkel, and L. Winsberg, Phys. Rev. **118**, 781 (1960).
[18] L. Winsberg, Phys. Rev. **95**, 198 (1954).

that the measured cross section for In^{113m} is much less than the total cross section for the isotope (Table II and Fig. 1). This reasoning may not be valid for $In^{115}(p,p')In^{115m}$ or, indeed, for $In^{115}(p,pn)In^{114m}$, both being rather special reactions.

In the cascade calculation referred to here, the nuclear density is assumed to drop abruptly to zero at the surface.[14] Since this assumption is not realistic,[19] we should not be surprised at the lack of agreement shown in Table III for the (p,pn), (p,p'), and $(p,p\pi^+)$ reactions. These three reactions, and others like them that can be attributed to a single collision inside the nucleus, should be especially sensitive to the nature of the nuclear surface. They are expected to occur only rarely in the interior of the nucleus because of the probability that the products of the initial collision will interact further to yield a different final nucleus.

The ratio given in Table III for the $(p,p\pi^+)$ reaction, namely zero, is probably not significant because of the statistical uncertainty of the calculation.

The cross section for the formation of Be^7 has been measured only at 6.2 Bev (Table II). No calculation of the cascade process has been made at this energy. It is, therefore, not possible to make a comparison of the type just presented. The value of the cross section, 14.1 mb, appears to be in line with the values measured by Baker, Friedlander, and Hudis[20] with 3.0-Bev protons incident on a variety of targets, including $Ag^{107,109}$. In their study, little or no change was found in the values of the cross section as a function either of the target or the energy from approximately 2 to 3 Bev with the exception of gold. These results were analyzed by Hudis and Miller in terms of the two-stage mechanism discussed here,[21] namely, a prompt-cascade process followed by evaporation of light particles including Be^7. They were able to account for much, if not most, of the cross-section value by this mechanism for proton energies up to 2 Bev. As we have just seen, this type of calculation fails to account for the (p,pxn) and $(p,2pxn)$ reaction at 2 Bev. A calculation that appears to account for one type of reaction and not another is clearly unsatisfactory.

B. Comparison Based on Shell Model and Diffuse Nuclear Surface

The cross sections of (p,pn), (p,p'), (p,n), and $(p,p\pi^+)$ reactions are expected to be especially sensitive to the initial interaction. The (p,pn) reaction is thought to occur primarily by a direct collision with a surface nucleon (see reference 1 for a discussion of this point). This is probably true of the (p,n) and $(p,p\pi^+)$ reactions also. (The production of the isomer of the target nucleus can occur by other types of reaction as well.) According to this viewpoint, two factors are important: (a) The structural details of the target nucleus, especially its surface, and (b) the nature of the collision between nucleons and between mesons and nucleons. By taking these factors into account, Benioff has been able to analyze measurements of (p,pn) reactions induced in a variety of targets by multi-Bev protons.[2] These calculations were made with harmonic-oscillator wave functions.

We can use his results to calculate the cross sections of the reaction $In^{115}(p,pn)$ to produce both the isomeric and the ground states of In^{114}. The value of the radius parameter, used for this calculation, is 1.07×10^{-13} cm.[19] The cross sections for the formation of In^{114m} are calculated in this way to be 44 ± 5 mb at 4.1 Bev, as compared to the experimental value of 57 ± 17 mb, and 41 ± 5 mb at 6.2 Bev, as compared to the experimental value of 59 ± 18 mb. The errors indicated for the calculated values are Benioff's estimate of the uncertainty of the total proton-neutron collision cross sections plus that due to the possible contribution of processes that follow the initial interaction.[2] Other uncertainties in the calculation are not included in the indicated error. The uncertainty indicated in the experimental values is the 30% error previously assigned. Because of the possible contribution of secondary reactions in thick targets, the value of 70 mb at 6.2 Bev is not included in the average.

The calculated and experimental values agree within the indicated uncertainties. This calculation has not been made at 2 Bev. At this energy we would expect a slightly larger calculated value than for the higher energies because of the larger total p-n collision cross section and the smaller meson multiplicity. The latter effect would allow a greater probabliity for the products of the initial interaction to escape.

At 4 and 6 Bev, the calculated cross section for the formation of the ground state of In^{114} is 5 mb, or approximately 10% of the total (p,pn) cross section. The calculation of the isomer ratio is based on reference 2. Apparently, the high-spin isomer is formed in preference to the low-spin isomer.

CONCLUSION

The preceding discussion may be summarized as follows:

(a) The values of the cross sections for the formation of indium and cadmium isotopes are essentially constant for incident-proton energies from 1.0 to 6.2 Bev. Possible exceptions are the values for Cd^{115} and In^{115m} at 1.0 Bev.

(b) The values of all the cross sections as calculated on the basis of the Fermi-gas model with constant nuclear density at 2 Bev are too small, compared to the experimental values. There is good agreement at 1 Bev for nuclides with mass number less than 113.

(c) The calculation for the reaction, $In^{115}(p,pn)In^{114m}$, at 4.1 and 6.2 Bev, made by taking into account the

[19] R. Hofstadter, Annual Review of Nuclear Science (Annual Reviews, Inc., Palo Alto, California, 1957), Vol. 7, p. 231.
[20] E. Baker, G. Friedlander, and J. Hudis, Phys. Rev. **112**, 1319 (1958).
[21] J. Hudis and J. M. Miller, Phys. Rev. **112**, 1322 (1958).

details of the nuclear structure of indium, agrees with the experimental values of the cross section within the uncertainties of the measured and calculated values. The corresponding reaction to form the ground state of In^{114} is calculated to be approximately 10% of the total (p,pn) cross section.

It is obvious from these observations and from the results of the preceding study on iodine[1] that our understanding of nuclear reactions induced by high-energy particles is incomplete.

Thus, processes other than direct interactions may contribute to these reactions in which only a small amount of energy is transferred to the nucleus. An example of this is Coulomb excitation of the target nucleus to the isomeric state in the case of the (p,p') reaction. Presumably, the cross section for such a process would depend sensitively on the spins of the ground and excited states. Several other targets, in addition to indium, are suitable for such a study. Excitation of the giant resonance, which has been observed with gamma-ray irradiation,[22] probably can occur with high-energy charged particles. This process could lead to the loss of one or two units of mass by the target nucleus. The good agreement found for the cross section of the (p,pn) reaction, calculated by means of Benioff's treatment,[2] with the experimental value suggests that this process does not contribute in an important way to the (p,pn) reaction. A comparison of (n,n') reactions, which cannot involve Coulomb excitation, with the (p,p') reaction, which can, should provide direct information on the importance of Coulomb excitation.

The (p,n) and $(p,p\pi^+)$ reactions require some kind of direct interaction between the incident proton and a nucleon in the target. The (p,n) and (p,p') reactions can proceed by way of elastic and inelastic p-p and p-n collisions, while the $(p,p\pi^+)$ reaction can occur only by means of an inelastic process. Thus the study of these three reactions with various targets affords an opportunity for assessing the relative importance of elastic and inelastic nucleon-nucleon collisions and of processes such as Coulomb excitation. A careful investigation of the energies the retained nucleon may have is needed. For this purpose more information on excited nuclear states than is now available is certainly desirable. An adequate study of $(p,p\pi^+)$ reactions requires the careful analysis of inelastic p-p scattering data. Because this is a major effort in itself, we have not attempted to do this.

The over-all calculation for (p,pxn) and $(p,2pxn)$ reactions has been made only for the Fermi-gas model of the nucleus. The results of the study reported here on indium and in the preceding paper on iodine[1] indicate that such an analysis predicts the correct cross sections of these reactions for x greater than 1 at energies of 1 Bev and less with few exceptions and fails to do so at 2 Bev. The excitation functions of most reactions that have been studied in the multi-Bev region of proton energies are constant within experimental error.[1,23] It is difficult for us to explain these observations except that there are serious defects in the cascade calculations for incident-proton energies above 1 Bev. The inclusion of a proper description of the nuclear surface is, of course, required in the calculation. However, we cannot see that this by itself will lead to the prediction of constancy in the excitation functions at the higher energies.

Perhaps the assumption, basic to the calculations, that nucleon-nucleon scattering inside a nucleus is in no essential way different from that for free nucleons, except for exclusion, is incorrect. It would be interesting to see what modifications in this assumption lead to better agreement with the experimental results. Meson production and readsorption is presumably an effective means for producing nuclear excitation. Therefore, a possible modification in the calculations would be to keep the meson multiplicity constant in the multi-Bev range of incident proton energies. Whether this improves the comparison or not remains to be seen.

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